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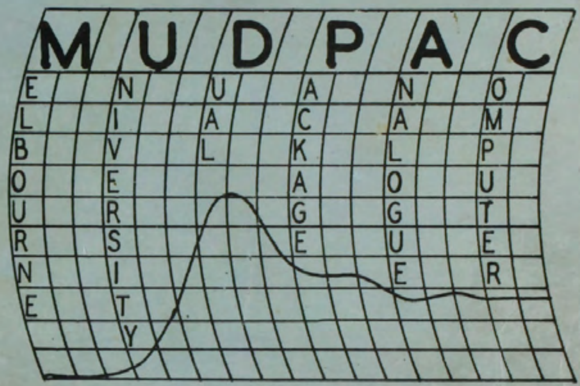
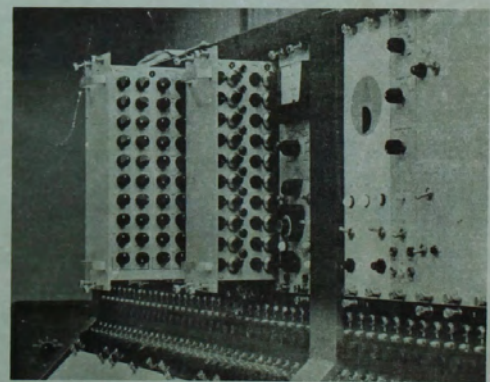
UNIVERSITY OF MELBOURNE FACULTY OF ENGINEERING

ANALOGUE COMPUTATION LABORATORY



OPERATOR'S MANUAL

Compiled by: E.A. King-Smith



1st Edition

October, 1963

UNIVERSITY OF MELBOURNE FACULTY OF ENGINEERING

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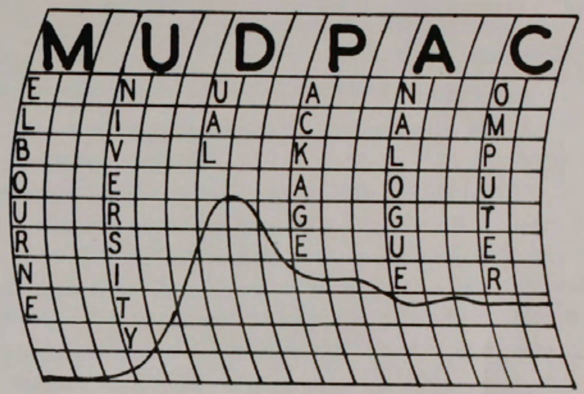

OPERATOR'S MANUAL

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Registered Number ....9.......

Laboratory Staff:

		Ext.
Officer-in-Charge:	(University: 34-0484)	
Technical Officer:	Mr. H. Taylor	330
Bookings:		330
Special Enquiries:	Mr. E. A. King-Smith	751

1st Edition October, 1963

FOREWORD

This Operator's Manual has been compiled to provide three kinds of information to actual and prospective users of the Engineering Faculty analogue computer MUDPAC.

Section I sets out information on the installation. Also in this section are contained the details of administration through which it is intended to provide efficient service to users.

Section II is abstracted from relevant sections of the manufacturer's Service Manual for the computer. This contains sufficient information for the average user to help him through the initial familiarization period and generally to guide him in later, more serious work. The particular practice example included, that of a second order linear system, has been found to be one of the best introductions to the computer. The later sections on using multipliers, function generators and non linear groups will enable the best use to be made of these facilities.

Section III comprises information on peripheral equipment for use with the computer, including operating instructions for each of the items normally available.

The co-operation of the various manufacturers in permitting the abstraction of suitable sections of their publications for use in this Manual is gratefully acknowledged.

Suggestions for the improvement in layout and/or content of this Manual will be welcomed.

E. A. King-Smith October, 1963.

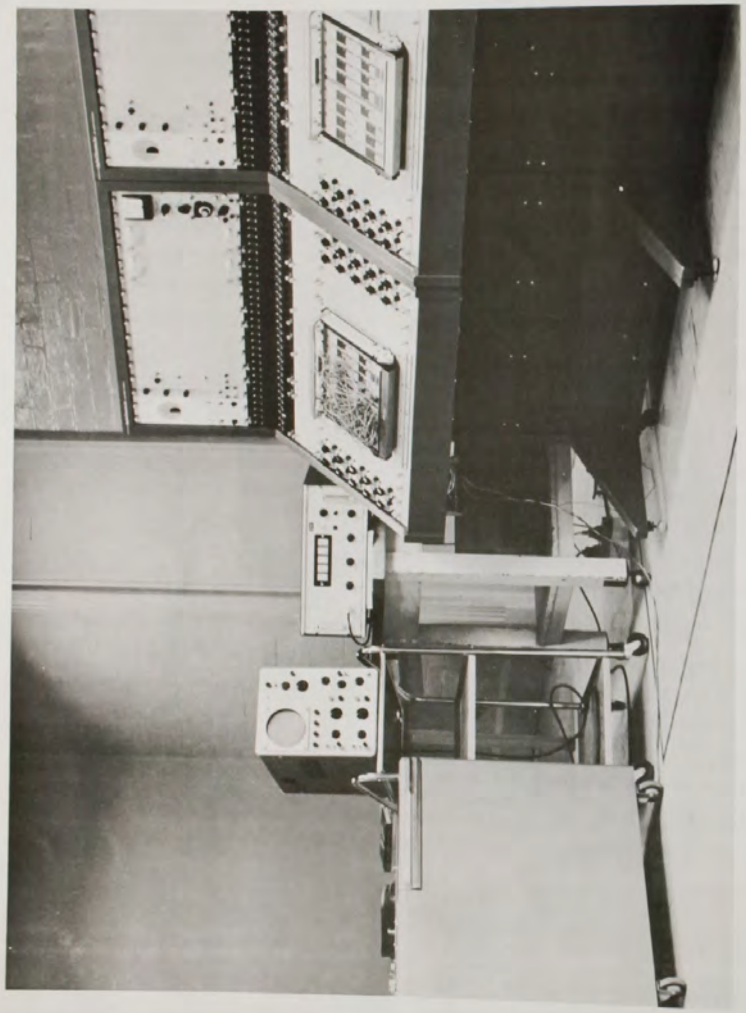
MUDPAC Manual

CONTENTS

SECTION I - GENERAL AND ADMINISTRATIVE INFORMATION

SECTION II - COMPUTER OPERATION

MUDPAC Manual



MUDPAC Installation with Peripheral Equipment - Multichannel, Pen Recorder, Twin-beam Oscilloscope and Digital Voltmeter

SECTION I - GENERAL AND ADMINISTRATIVE INFORMATION

1. What is MUDPAC?

The Melbourne University Dual Package Analogue Computer is a medium-sized analogue computer purchased with a special grant made available by the Australian Universities' Commission in 1960. The installation has been set up primarily as a research tool for the Faculty of Engineering, but it is made available to other University departments and outside users subject to certain conditions.

The computer was supplied by Applied Dynamics Inc., of Ann Arbor, Michigan, U.S.A., and delivered during April, 1961. Acceptance tests were completed in May, and the computer placed in trial service. On 1st August, 1961, it was released for general use.

It is located in the Analogue Computer Laboratory, in the Old Building of the Engineering School, on the ground floor, north wing (under the Library).

2. Analogue and Digital Computers

The word 'computer' in its modern losse context usually refers to a digital computer. This type of machine operates basically with whole numbers, and its operations are a combination of logic and arithmetic performed at very high speed. The digital computer therefore finds extensive use where arithmetic and algebra are the prime operations, such as in accounting, statistics, linear programming, simultaneous algebraic equations, etc.

The digital computer can also be used to solve problems which involve fundamentally continuous functions, but, to do this, the operations must be broken down into a series of very small steps, so that arithmetic methods may be used.

The analogue computer by contrast operates basically with continuous functions, and has been developed to deal specifically with problems involving such functions. Particularly amongst these are differential, integral and integro-differential equations.

Where engineering accuracy of 1 per cent, sometimes better, will suffice, the modern analogue computer provides a flexible tool for solving complex problems of dynamic systems. This it can do very rapidly and with reasonably simple programming, and for a relatively moderate outlay. A low-priced digital computer, if it can accept the problem, will take a long time to produce the same solution; alternatively an expensive digital machine will be required to cut down the computation time on these problems to something reasonable.

3. Problems Suitable for Analogue Computation

The analogue computer has been most successfully applied to those fields which are describable in terms of differential equations, such as

Differential equation solutions, linear and non-linear
Electric power system analysis
Circuit design
Servo system investigations
Vibration analysis, mechanical and aerodynamic
Aircraft flight characteristics and autopilots
Chemical plant simulation, and controller design
Chemical reaction kinetics
Nuclear reactor performance and control
Structural analysis
Hydraulic problems, surface and underground flow
Biological system investigations
Economic system behaviour.

Other miscellaneous applications for which it is well suited are

Parameter optimization
Auto-correlation and cross-correlation functions
Measurement of power spectra and cross-spectral density functions
Fourier transformations and transform inversion
Plotting and mapping transformations
Curve fitting.

Although not its most effective field of employment, this type of computer can also be used for particular problems of an algebraic nature, such as

Eigenvalue problems
Linear algebraic equations
Evaluation of Determinants
Matrix inversion
Roots of polynomials
Transcendental equations
Linear programming
Non-linear programming.

4. Bookings

MUDPAC was purchased primarily as a research tool for the Engineering Faculty. However, since it is rarely loaded fully for long periods by the various engineering research projects which are suitable for it, the remaining time is normally made available to other users outside this Faculty.

Prospective users are encouraged to book time ahead, and, subject to the nominated time being available, and with due regard to priorities as decided from time to time when the computer is heavily loaded, bookings may be made up to one month in advance.

Since there is normally a diversity of loading, the machine will rarely be occupied continuously for long periods, and intending users may reasonably expect to find time available at shorter notice than indicated above, or even at no notice at all. However, booking well ahead will always be the most satisfactory procedure.

The telephone extension (University) for computer bookings is 330. Any special enquiries should be directed to Mr. E. A. King-Smith of the Electrical Engineering Department (extension 751 or 330).

IN ORDER TO REDUCE UNNECESSARY IDLE COMPUTER TIME TO A MINIMUM, COMPUTER USERS ARE REQUESTED TO CANCEL UNREQUIRED TIME AS FAR AHEAD AS POSSIBLE. THREE DAYS' NOTICE OF CANCELLATION WILL USUALLY ENABLE THE TIME TO BE REALLOCATED TO OTHER PROSPECTIVE USERS. THE CO-OPERATION OF ALL USERS IN THIS RESPECT WILL ENSURE EFFICIENT ALLOCATION OF AVAILABLE COMPUTER TIME.

5. Operator's and Service Manuals

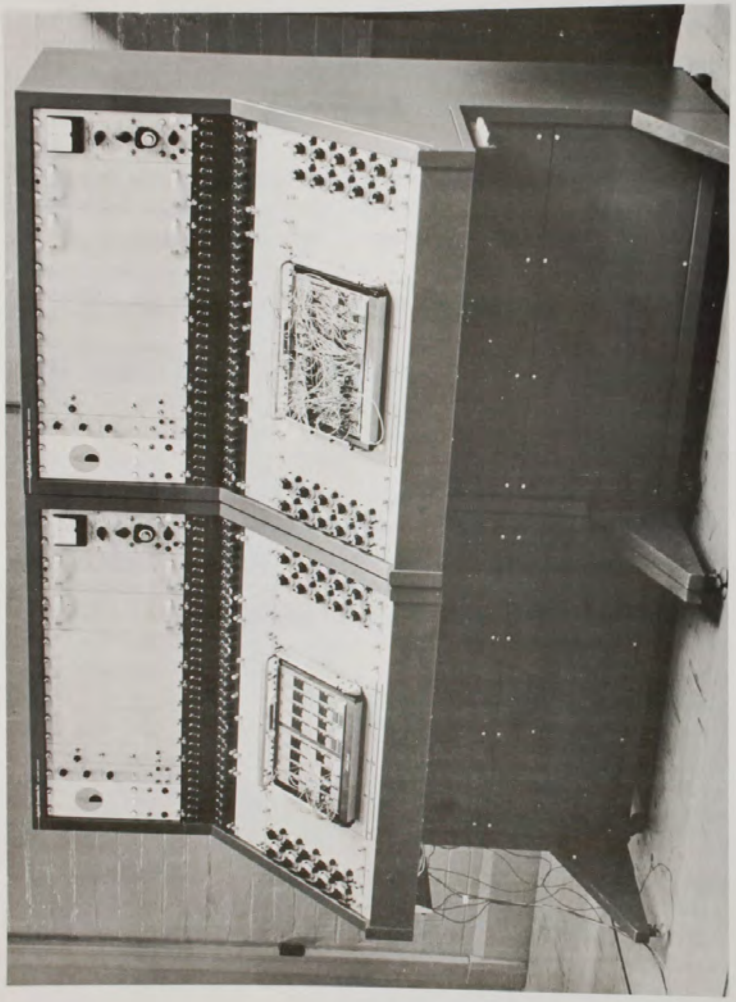
For normal usage of the computer, this Operator's Manual will generally be found adequate. Additional copies of the Manual are available from the Analogue Computation Laboratory at £2 per copy. This price includes the issue of future amendements as long as the edition is current.

More detailed descriptions of the operation of the computer and its various components, calibration and test procedures are contained in the Service Manual for the Computer. A number of copies of the Service Manual are held in the Laboratory for issue on loan to computer users as required. Copies may be purchased for private use at £5 per copy.

Sales of these publications, or their loan, is through the computer Technical Officer (Mr. H. Taylor).

6. Ownership Record Sheets

At the back of this Manual will be found a number of sheets, each divided into several slips, to be used in notifying the Laboratory whenever the publication changes ownership. It is most important that these be used properly if successive owners are to always be in possession of a Manual with all amendments as issued from time to time.



Twin Consoles of the MUDPAC Installation

7. MUDPAC Capacity and Facilities

The computer installation comprises two virtually identical modules, each an ADI model AD-1-64-PB self-contained computer. Each module contains the same facilities, the only difference being that Module I can be set to operate as the master unit to control Module II as the slave when both units are required to work together as one double-sized computer for extensive or complex problems.

The ultimate capacity of the installation is, basically -

	Each Module	Whole Installation
Operational Amplifiers	64 (max. 22 integrators)	128 (max. 44 integrators)
Multipliers	8	16
Arbitrary Function Generators	4	8
Non-linear Function Groups	3	6
Potentiometers	80	160

The present installation comprises -

	Each Module	Whole Installation
Operational Amplifiers	44 (max. 22 integrators)	88 (max. 44 integrators)
Multipliers	6	12
Arbitrary Function Generators	3	6
Non-linear Function Groups	2	4
Potentiometers	60	120

Built in facilities include -

- Manual precision potentiometer setting by null bridge
- Audible overload alarm
- Automatic hold on overload
- Repetitive high-speed operation
- Time markers
- Delays for recorder motor start and pen drop.

MUDPAC Manual

8. Peripheral Equipment

The present output facilities comprise -

1 Double-beam Oscilloscope (persistent screen)

1 4-channel Pen Recorder with Events Marker (to 200 c.p.s., ± 7 cm. deflection)

1 Plotting Table (25 cm. x 38 cm.)

1 Digital Voltmeter (join facility with Electrical Engineering Department)

Other facilities such as an additional oscilloscope, pen recorders, waveform generators, random function generators, etc., may also be available at certain times, when they are not required for their normal commitment to other engineering laboratories. These, however, cannot be relied on to be available at any particular time.

9. Programming Sets

Those using MUDPAC regularly or for extended projects are encouraged to purchase their own patchboards and patchcord sets.

The few sets held in the Analogue Computation Laboratory can only be made available on loan on the basis of "return on demand" in order to maintain accessibility to as many users as possible. Even so, there is often delay in obtaining programming facilities at the commencement of a project if the previous user does not return his boards promptly on request.

This also means that storage of programmes on the laboratory patchboards cannot be guaranteed to any user for the period of running his particular problem or project unless the computer is thereby occupied continuously.

Two programming sets have been chosen suitable for use with MUDPAC - a "standard" set and a "restricted" set.

The "standard" set is sufficient to cover all programming needs for complex problems utilising computer capacity up to the complete facilities of one module. The "restricted" set is suitable for use when only about half the capacity of one module will be employed.

If the entire installation of two modules is to be used, one "standard" and one "restricted" set will usually cover all requirements.

The design of a suitable container for the storage of one patchboard and a "standard" or "restricted" patchcord set is available from the Laboratory. (These sets are purchasable through the laboratory. Prices and delivery information is available on request).

Details of each set are as follows:

"STANDARD" MUDPAC PROGRAMMING SET

No.	Description	Cord Colour	A-MP Part No.
Patchboard			
1	Patchboard 1632-hole	-	695009-2
Patchcords			
100	Shunt loops	red	395 151/2
75	Patchcords 5"	red	" 223/2
65	" 7"	grey	" " /3
60	" 9"	blue	" " /1
50	" 11"	green	" " /4
30	" 13"	yellow	" " /5
15	" 15"	orange	" " /6
10	" 19"	black	" " /7
2	Squids 3" 4-pin	orange	495 297/1
3	" " 6 "	"	" 299/1
1	" " 8 "	"	" 301/4
2	" 5" 4 "	red	" 297/3
3	" " 6 "	"	" 299/3
1	" " 8 "	"	" 301/5
2	" 7" 4 "	grey	" 297/4
3	" " 6 "	"	" 299/5
1	" " 8 "	"	" 301/1
2	Y-cords 7" 3 "	grey	" 396/1
3	" " 5 "	"	" 398/1
1	" " 7 "	"	" 400/1
2	" 11" 3 "	green	" 396/3
3	" " 5 "	"	" 398/3
1	" " 7 "	"	" 400/3
2	" 15" 3 "	orange	" 396/5
3	" " 5 "	"	" 398/5
1	" " 7 "	"	" 400/5

"RESTRICTED" MUDPAC PROGRAMMING SET

No.	Description	Cord Colour	A-MP Part No.
Patchboard			
1	Patchboard, 1632-hole	-	695009-2
Patchcords			
60	Shunt loops	red	395 151/2
35	Patchcords 5"	"	" 223/2
30	" 7"	grey	" 223/3
30	" 9"	blue	" 223/1
25	" 11"	green	" 223/4
15	" 13"	yellow	" 223/5
5	" 15"	orange	" 223/6
5	" 19"	black	" 223/7
1	Squids 3" 4-pin	orange	495 297/1
2	" " 6 "	"	" 299/1
1	" " 8 "	"	" 301/4
1	" 5" 4 "	red	" 297/3
2	" " 6 "	"	" 299/3
1	" " 8 "	"	" 301/5
1	" 7" 4 "	grey	" 297/4
2	" " 6 "	"	" 299/5
1	" " 8 "	"	" 301/1
1	Y-cords 7" 3 "	grey	" 396/1
2	" " 5 "	"	" 398/1
1	" " 7 "	"	" 400/1
1	" 11" 3 "	green	" 396/3
2	" " 5 "	"	" 398/3
1	" " 7 "	"	" 400/3
1	" 15" 3 "	orange	" 396/5
2	" " 5 "	"	" 398/5
1	" " 7 "	"	" 400/5

10. Programming Assistance

At present there is no full-time member of staff available to give programming assistance. The Technical Officer, Mr. H. Taylor, is available to help with initial familiarization with the computer, and with routine programme trouble-shooting, as well as providing emergency computer maintenance service.

Until the officer-in-charge is appointed, Mr. E. A. King-Smith of the Electrical Engineering Department should be contacted with any special enquiries, although he will not be available for detailed programming assistance. (See Section for Programming Courses).

11. Programming Courses

Programming courses for MUDPAC are conducted from time to time, their duration and content varying according to the requirements of participants.

Other theoretical and practical courses, usually in the nature of regular University subjects, or parts thereof, may also be available to interested persons.

Details of any of these courses may be obtained from Mr. E. A. King-Smith, Ext. 751.

12. Recording and Plotting Paper

Paper for use in the multichannel pen recorders and 2 co-ordinate plotting tables is reasonably expensive, and each department or outside user is required to purchase his own supplies. Cost of the various papers and their sources of supply is as follows:

Equipment	Description	Supplier	Cost
PACE 1100E 2-coordinate Plotting Table	25 cm x 38 cm, mm. ruling Pkts. of 100 sheets Ident. K & E 47 1513	Electronic Associates, 87 Alexander Street, Crows Nest, N.S.W.	£5. 12. 6
Mosley 2 coordinate Plotting Table	Heavy grade Pkts. of 100 sheets Ident. H100/150	Sample Electronics (Vic.) Pty.Ltd., 9 Cremorne Street, Richmond, Vic.	£3. 13. 9
	Light grade Pkts of 100 sheets Ident. L100/150		£3. 10. 6
	Roll chart 100 ft. length Ident. 2280011A		£4. 5. 0

Offner 2-channel Pen Recorder	Rolls of 500 ft. Ident. 652PG50B	Sample Electronics (Vic.) Pty.Ltd., 9 Cremorne Street, Richmond, Vic.	£3. 8. 3
Offner Multi-channel Pen Recorder	(a) 6-channel, ruled. Rolls of 500 ft. Ident. 656PG50B	"	£11. 5. 0
	(b) 8-channel, ruled. Rolls of 500 ft. Ident. 668PG50B	"	£12. 13. 3
Both 2-channel Pen Recorder	Rolls of 150 ft. Ident. 852	Stanford X-ray (Vic.) Pty.Ltd., 256 Wellington St., Collingwood.	£1. 11. 6
Both 4-channel Pen Recorder	Rolls of 150 ft. Ident. 854		£3. 0. 9

These items may be purchased direct from the suppliers indicated, or via the Laboratory.

13. <u>Work Records</u>

In order that systematic records may be kept of work carried out on this computer, each user is requested to make out a standardized record sheet for each project if useful results are obtained. In this way it is expected that a valuable library of information will be built up, such that future users may benefit from the experience of those using the installation for similar or allied problems before them.

Each record will be allocated a reference number consisting of two or three code letters indicating the user, followed by two figures indicative of the year, then a serial number. This will lead to a simple filing procedure and allow convenient cross-referencing. Such cross-referencing between records should be indicated whenever convenient, as this will enhance their value to those who might use them as source material at a later date.

A typical reference number is CE 62/17 which indicates that the record refers to a problem set up by the Chemical Engineering Department in 1962, being No. 17 for that year originating from that department.

Two-letter prefixes will be used for University departments, three-letter prefixes for outside organizations. These will be mnemonic as far as practicable. The list of prefixes below are applicable at this date.

<u>University of Melbourne</u>

Agricultural Engineering	AE
Chemical Engineering	CE
Chemistry	CH
Civil Engineering	CI
Economics and Commerce	EC
Electrical Engineering	EE
Industrial Engineering	IE
Mathematics	MA
Mechanical Engineering	ME
Metallurgy	MT
Physics	PS
Physiology	PY
Surveying	SU

<u>Outside Organizations</u>

CSIRO, Division of Industrial Chemistry	CIC
R. Medding & Associates	RMA
Philips Electrical Industries	PEI
University of New South Wales	UNS

14. Scheduled Maintenance Periods

In order to provide preventive maintenance, certain periods have been set aside for regular servicing. During these periods, the computer will not be available for use. The maintenance schedule is set out below and prospective users should not seek to book the computer at these times.

The computer will normally be available daily from 9.30 a.m. to 5.00 p.m.

The times at which it will not be available are as follows:-

	Time	Reason
1.	Each day from 9.00 a.m. to 9.30 a.m.	Daily check and calibration
2.	Each Monday until 1.00 p.m.	Weekly check and service of all facilities
3.	The first Monday of each month (all day)	Complete monthly check of all facilities.
4.	The first Monday and the following Tuesday in May, August, & November (all day)	Quarterly minor overhaul
5.	The whole of the week commending with the first Monday in February	Annual complete overhaul

15. Out-of-Hours Operation

There are 68 module hours available in the normal working week, less when monthly or quarterly servicing is carried out.

It may be possible on occasions to make special arrangements for out-of-hours working. Usually there will be no Technical Officer or other staff present at such times, and operation will be without provision for unscheduled maintenance in case of breakdown (which is fortunately rare) or routine trouble-shooting of inoperative programmes.

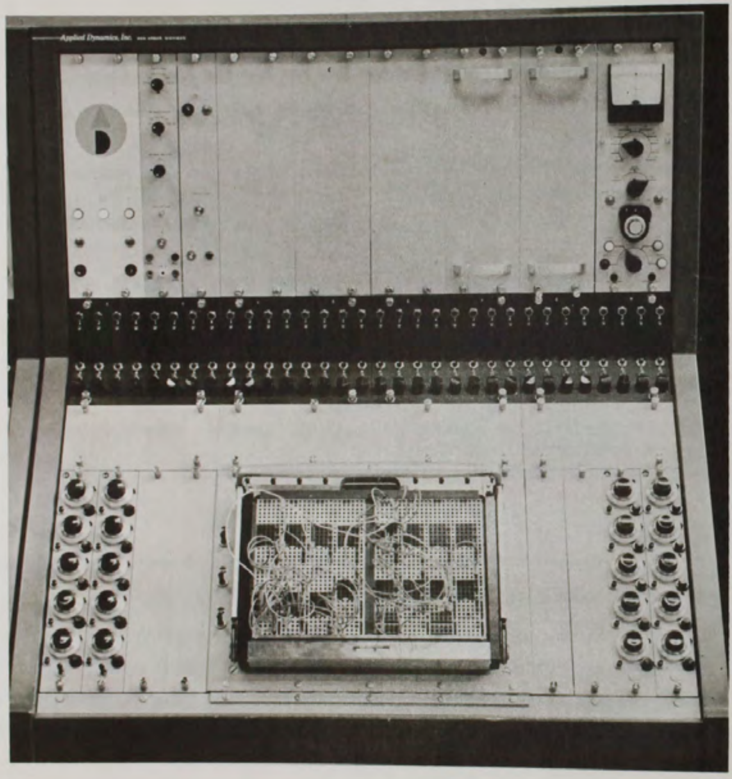


Figure 1-1. Model AD-1-64PB Analog Computer cabinet.

16. Retention of Potentiometer and DFG Settings

Arrangements may be made to preserve certain potentiometer and diode function generator (DFG) settings between successive sessions of running a particular programme when only a short time elapses between sessions.

These arrangements will in all cases be dependent on no other user requiring the same facilities in the interim, and the retention of settings therefore cannot be guaranteed.

Requests for retention of settings must be in writing on the proper form.

Settings of potentiometers adjacent to the patch panels cannot be retained.

All controls whose settings are being retained will be placarded on the computer, and other computer users must respect these notices.

The Officer-in-Charge is the only person who can authorize the retention of potentiometer or DFG settings, or the destruction of these settings in the absence of the user making the original retention request.

1. GENERAL DESCRIPTION

The Applied Dynamics Analog Computer, Model AD-1-64PB, is capable of solving both linear and nonlinear ordinary differential equations.

MUDPAC consists of two such computing consoles each of which contains up to 64 operational amplifiers, 80 coefficient pots, 16 electronic multipliers, 8 diode function generators, and 20 special diode networks. The problem is wired by means of patch cords on the 1632-hole removable patchboard shown in the center of Figure 1-1. To the left and right of the patchboard are panels of coefficient potentiometers, 5 pots to each 2¼" wide panel . Above the patchboard are the amplifier monitor panels (the black area in the Figure). Each panel contains overload indicators and balance-adjust knobs for 8 amplifiers.

Above this area and across the top of the cabinet front are spaces for eight modules, 4½" wide by 14" high. This is the standard size for all AD-1 component modules, except that some modules are half-width (2¼" x 14"), e.g. the coefficient pot panels and the Repetitive Control Module.

The Power Supply Module can be seen in the upper left corner of the cabinet in Figure 1-1. This module supplies power for 32 operational amplifiers and the ±100 volt reference-supply amplifiers. For more than 32 amplifiers a second power supply is required, and is located in the bottom of the cabinet. It is controlled by the switches on the front of the first power supply.

The Control Module is located in the upper right corner of the cabinet and contains the main computer control switch (BAL. CHK., RESET, OPERATE, HOLD), a 0.05% 10-turn reference potentiometer against which coefficient pots are set by means of a null circuit, and a meter for use as a null indicator and for direct monitoring of amplifier outputs and other voltages. The precision null pot can also be used to read any amplifier output to 0.1% accuracy.

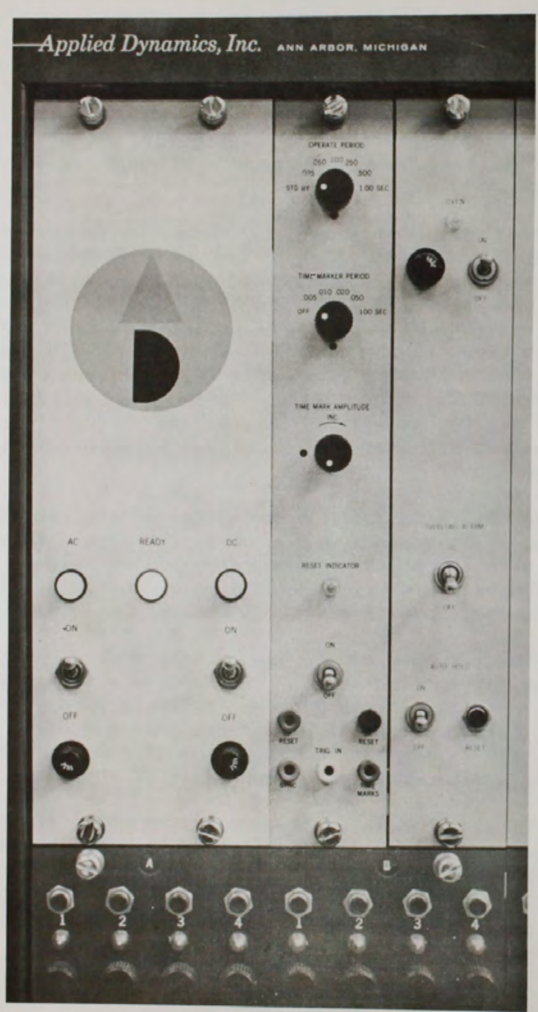


Figure 1-2
Power Supply, Repetitive Operate, and Auxiliary
Control Panels

To the left of the Control Module in Figure 1-1 are shown the front panels for the Diode Function Generator and Coefficient Pot Modules which become accessable when the front panels are pulled forward on sliding rails.

To the right of the Power Supply Module in Figure 1-1 is the Repetitive Control Module, used to provide the integrator reset pulses in addition to oscilloscope sync pulses and timing markers when repetitive operation is required.

Located in the upper left hand section of each computer next to the power supply and repetitive control panel is an auxiliary control panel. This panel controls the special features built into these computers.

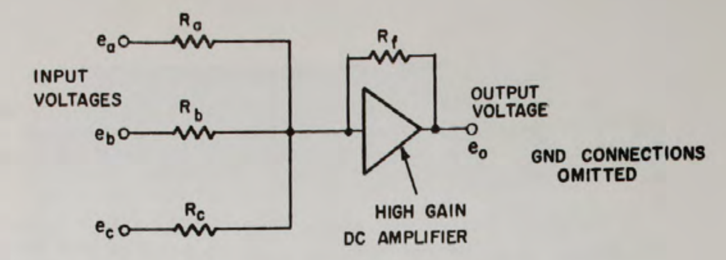


Fig. 2-1 - Summing Amplifiers - Schematic

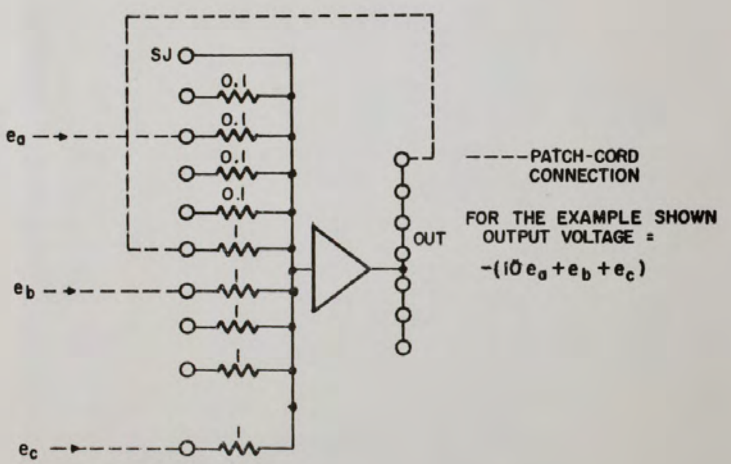


Fig. 2-2 - Summing Amplifier - Patchboard Connections

2. Basic Theory

The basic building blocks of the electronic differential analyzer are the dc operational amplifiers. These are high gain dc feedback amplifiers which can be used to multiply voltages by a constant, add voltages, and integrate voltages with respect to time. These various operations can be combined to solve ordinary linear differential equations, where the various terms in the equations are represented in the computer by voltages.

(a) SUMMING AMPLIFIERS

Consider the operational amplifier shown in Figure 2-1. It consists of a high gain dc amplifier with a feedback resistor R_f and input resistors R_a, R_b and R_c. To each of the input resistors are applied input voltages e_a, e_b, and e_c respectively. It is easy to show that the output voltage e_o is given to a high degree of accuracy by

$$e_o = -\left(\frac{R_f}{R_a} e_a + \frac{R_f}{R_b} e_b + \frac{R_f}{R_c} e_c \right)$$

i.e., the output voltage is proportional to the sum of the input voltages, with a sign reversal.

The actual patchboard hole connections and various input resistors for one of the AD-1 summing amplifiers are shown in Figure 2-2. Any of these resistors can be connected as a feedback resistor by patching from an OUTPUT hole to the appropriate input hole. In the example shown a 1 megohm feedback resistor has been chosen. Any of the other resistors are then available as input resistors to which input voltages can be fed. In Figure 1-3 voltages e_a, e_b, and e_c are fed into resistors of 0.1, 1, and 1 megohms. Hence the output voltage is $-(10e_a + e_b + e_c)$. Often several resistors can be combined in parallel to get resistor values not individually present. For example, if two 1 megohm resistors are used for feedback, the total feedback resistance is 0.5 megohms. In general, nonintegral gain factors can be obtained most easily by using the coefficient pots as input attenuators.

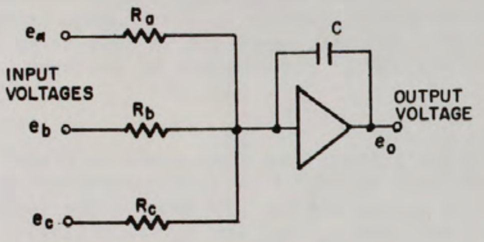


Fig. 2 - 3 - Summing Integrator - Schematic

(b) INTEGRATING AMPLIFIERS

Consider next the operational amplifier shown in Figure 2-3. Here a feedback capacitor C instead of a feedback resistor R_f is used. It is easy to show that to a high degree of accuracy

$$e_o = - \int \left(\frac{1}{R_a C} e_a + \frac{1}{R_b C} e_b + \frac{1}{R_c C} e_c \right) dt$$

i.e., the output voltage is proportional to the time integral of the sum of the input voltages, again with a sign reversal. The constant of proportionality for each input voltage is proportional to the reciprocal of the input resistance.

In the AD-1-64PB Computer there are 8 four-amplifier integrator-summer areas in the patchboard. Amplifiers 1 and 4 in each integrator-summer area are always summing amplifiers, while amplifiers 2 and 3 can be used as integrators or summers.

3. PATCHBOARD LAYOUT

The 1632-hole patchboard used in the AD-1-64PB Computer is split into two 816-hole sections, as can be seen in Figure 1-1. Each contains holes by which patch cords can be connected to inputs and outputs for up to 32 amplifiers and 40 coefficient pots, as well as multipliers, function generators, diode networks, and other components.

Each 816-hole section has 4 identical four amplifier integrator-summer areas across the top half of the board section, thus there is a total of 8 integrator-summer areas across the top half of the entire board. These areas are numbered A1 through H1 respectively, from left to right. In addition, the R.H. 816-hole section has 2 four-amplifier summer-multiplier and 2 four-amplifier summer-diode areas across the bottom half of the board section. These areas are numbered E2 through H2 respectively, from left to right.

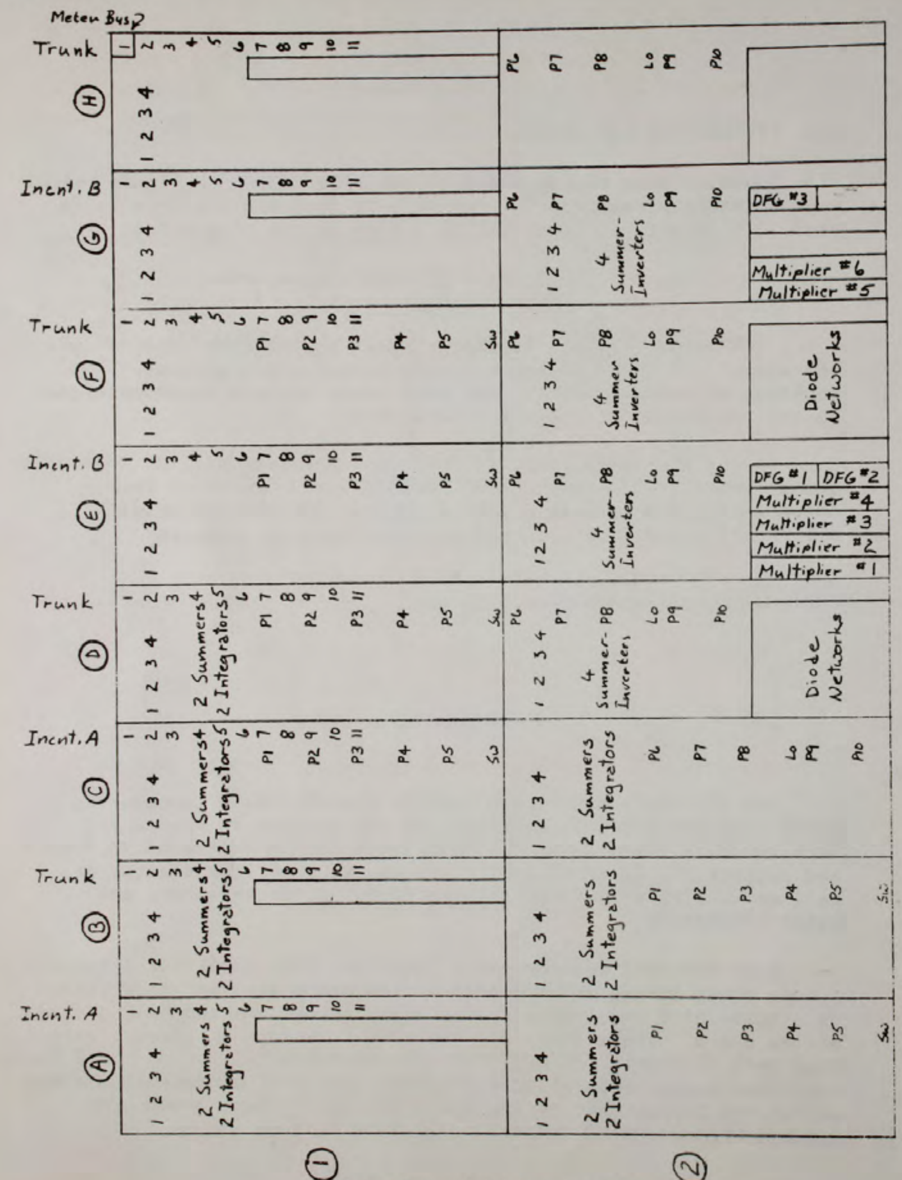


Figure 3-1 - Patch Panel Areas

The L.H. 816-hole section has 3 identical four-amplifier integrator-summer areas and one four-amplifier summer diode area across its lower section. These areas are identified as A2 through C2 and the lower part of D, respectively.

(a) Repetitive Operation

The repetitive operate switches for the upper integrator areas are arranged along the top of the patchboard frame, whilst those for A2, B2 and C2 areas are located to the left of this frame. Note that each switch controls both integrators within its designated area.

(b) Potentiometers

There are no potentiometers at present in areas A1, B1, G1 and H1. (These are reserved for future expansion). Note that types 1-5 pot panels, with function switches, are installed in areas C1, D1, E1, F1 (in potentiometer drawer), A2 and B2 (left of patchboard frame). Type 6-10 pot panels, without function switches but with no. 8 pot ungrounded at its lower end, are installed in areas C2, D2, E2, F2 (in potentiometer drawer), G2 and H2 (right of patchboard frame).

(c) Multipliers

Multipliers nos. 7 & 8 are not yet installed in area G2.

(d) Function Generators

Diode Function Generator no. 4 is not yet installed in area G2.

(e) Trunking

The holes numbered 1-11 (grey) in areas B, D, F & H are trunked through to the identical holes in the other console. These are used in programming when both consoles are slaved together.

(f) External Connections

Holes numbered 1-11 (grey) in areas A, C, E & G are brought out to a correspondingly numbered array of terminals at the rear of each console. In addition, A1-11 in each case is brought out in parallel to a set of terminals at the L.H. side of the Master console, and the R.H. side of the Slave console.

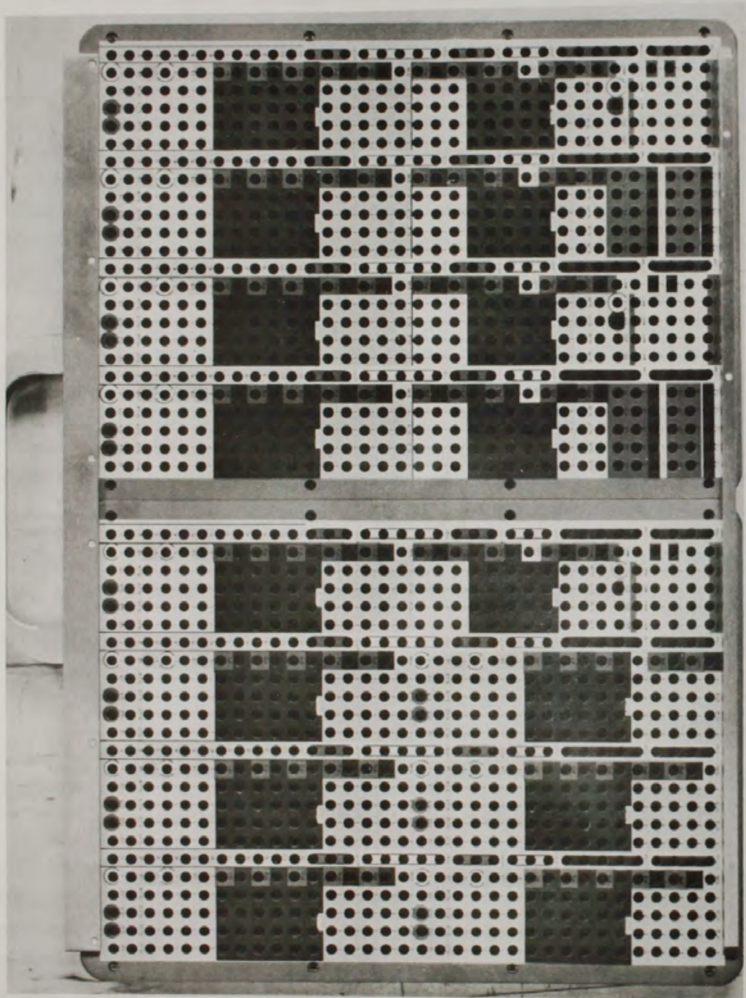


Figure 3-2 - Patch Panel

(g) Amplifier Rearrangement

By special arrangement amplifiers may be removed from one area and placed in another normally unfilled area, i.e., in one or more of areas E1, F1, G1, H1, to provide more integrator capacity.

(h) Integrator-Summer Area

Each of the 11 integrator-summer areas of the patchboard consists of a 5 x 17 matrix of holes which can provide patch cord connections to summing amplifier 1 (four 0.1 meg and five 1 meg input resistors), integrator-summer amplifiers 2 and 3 (each with four 0.1 meg and four 1 meg input resistors), and summing amplifier 4 (four 0.1 meg and five 1 meg input resistors), as well as connections to pots 1-5. An integrator-summer area of the batchboard is illustrated in Figure 3-3. In general, columns 1, 2, 3, and 4 of the integrator-summer area provide input and

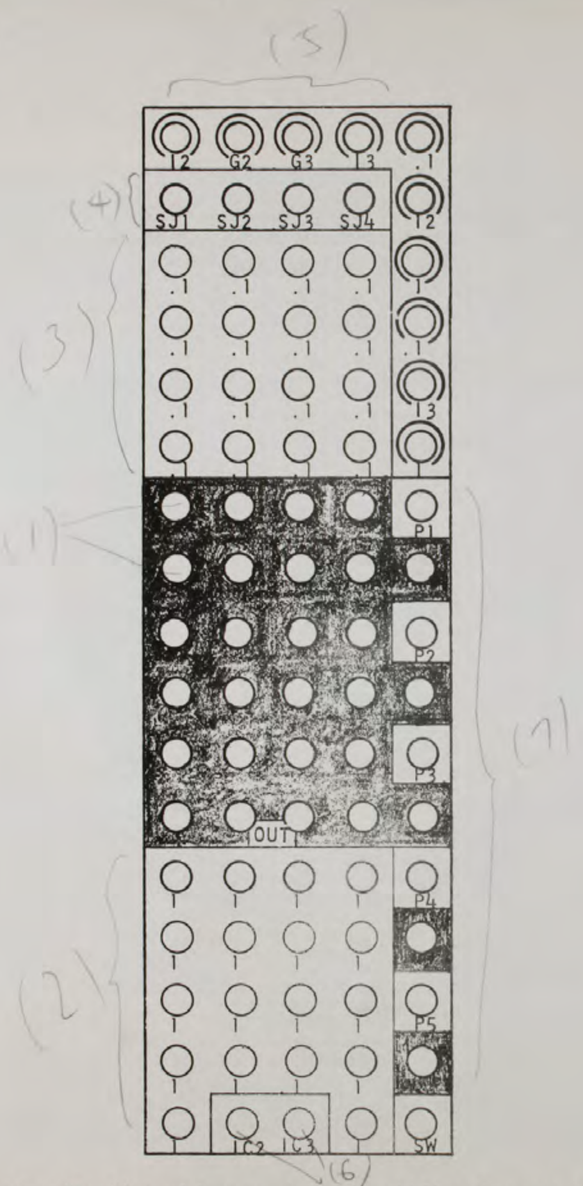


Figure 3-3. Patchboard Layout for 4-Amplifier Integrator-Summer Area.

output connections to amplifiers 1, 2, 3, and 4, respectively, while column 5 provides connections to the integrating capacitors and to coefficient pots 1-5. An exact description of the various connections follows.

(1) AMPLIFIER OUTPUTS. Across the center of the integrator-summer area is a 4 x 6 matrix of holes with black background labeled OUT at the bottom of the area. Column 1 provides six common connections to the output of amplifier 1, column 2 provides six common connections to the output of amplifier 2, column 3 provides six common connections to the output of amplifier 3, column 4 provides six common connections to the output of amplifier 4. These connections are shown in the overall integrator-summer area schematic in Figure 3-4.

(2) 1 MEGOHM INPUT RESISTORS. Directly below the black output area in Figure 3-3 is a 4 x 5 matrix with yellow background which provides connections to the 1 meg input resistors. Columns 1 and 4 provide connections for five 1 meg input resistors for summing-amplifiers 1 and 4, respectively. Columns 2 and 3 provide connections for four 1 meg input resistors for integrator-summer amplifiers 2 and 3, respectively. The single holes with grey background at the bottom of columns 2 and 3 are labeled IC2 and IC3 are the connections into which initial-condition voltages for integrators 2 and 3 are patched, respectively.

(3) 0.1 MEGOHM INPUT RESISTORS. Directly above the black output area in Figure 3-3 is a 4 x 4 matrix with white background which provides connections to the 0.1 meg input resistors. Columns 1, 2, 3, and 4 provide connections for four 0.1 meg input resistors for amplifiers 1, 2, 3, and 4, respectively.

(4) SUMMING-JUNCTION CONNECTIONS. Directly above the white 0.1 meg area is a row of 4 holes with blue background which provide connections, from left to right, to the summing junctions for amplifiers 1, 2, 3, and 4, respectively. This is the second row from the top of Figure 3-3 and the holes are labeled, respectively, SJ1, SJ2, SJ3, and SJ4.

(5) INTEGRATOR-SUMMER CONNECTIONS. The top row in Figure 3-3 has 4 holes labeled, respectively, I2, G2, G3, and I3. Holes G2 and G3 are surrounded by a red ring and provide connections to the input grid for amplifiers 2 and 3, respectively, as can be seen in the circuit schematic of Figure 3-4. Holes I2 and I3 are surrounded by a blue ring and provide connections to the reset-relay common for amplifiers 2 and 3, respectively, as is evident in Figure 3-4.

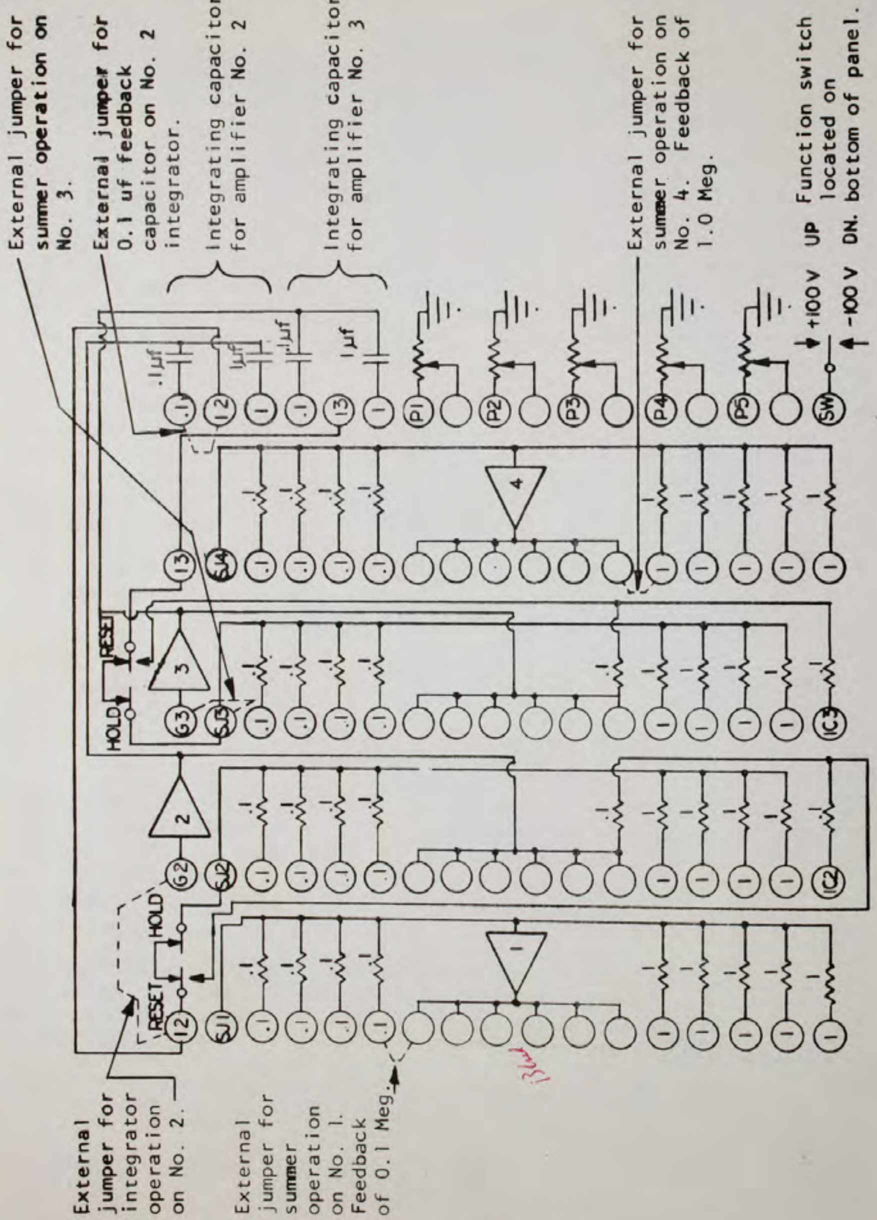


Figure 3-4 , Patchboard Circuit Schematic, Integrator-Summer Area.

The first 6 holes in column 5 of the integrator-summer area provide connections to the integrating capacitors for amplifiers 2 and 3. The 2nd and 5th holes from the top of column 5 are surrounded by a blue ring and are labeled I2 and I3, respectively; they provide connections to the reset-relay common for amplifiers 2 and 3, respectively. The 1st and 4th holes from the top are surrounded by a white and black ring and are labeled .1; they provide connections to the 0.1 mfd feedback capacitors for amplifiers 2 and 3, respectively, as shown in Figure 3-4. The 3rd and 6th holes from the top are surrounded by a yellow ring and are labeled 1; they provide connections to the 1 mfd feedback capacitors for amplifiers 2 and 3, respectively.

To connect amplifier 2 as a summer, a cord is patched from the hole labeled SJ2 to the hole directly above labeled G2. Similarly, to connect amplifier 3 as a summer a cord is patched from SJ3 to G3.

To connect amplifier 2 as an integrator with 1 mfd feedback capacitor a cord is patched from the hole labeled G2 to the hole to the left labeled I2; a second cord is patched from I2 (2nd hole from the top of column 5) to the hole directly below, labeled 1. If a 0.1 mfd capacitor is desired instead of 1 mfd. the cord from I2 is patched to the hole directly above labeled .1. Similarly, to connect amplifier 3 as an integrator a cord is patched from G3 to the hole to the right labeled I3; for a 1 mfd feedback capacitor a second cord is patched from I3 (5th hole from the top of column 5) to the hole directly below, labeled 1; for a .1 mfd feedback capacitor the cord from I2 is patched to the hole directly above labeled .1. The circuit details can be seen in the schematic of Figure 3-4.

(6) INITIAL-CONDITION CONNECTIONS. At the bottom of columns 2 and 3 in Figure 3-3 are two holes with grey background labeled IC2 and IC3. These provide initial condition connections for amplifiers 2 and 3, respectively, when connected as integrators. The negative of the desired initial condition voltage is patched into IC2 or IC3. If no voltage is connected the initial condition will be zero.

(7) COEFFICIENT-POT CONNECTIONS. The 7th through 16th holes down from the top in column 5 provide connections to coefficient pots 1 to 5. The pot input hole has red background and is labeled P_1 for pot 1, P_2 for pot 2, etc. In each case the pot output hole is directly below the input hole and has a black background. As shown in Figure 3-4 the input hole for each pot is connected to the high side of the pot, the output hole is connected to the pot wiper arm, and the low side of the pot is

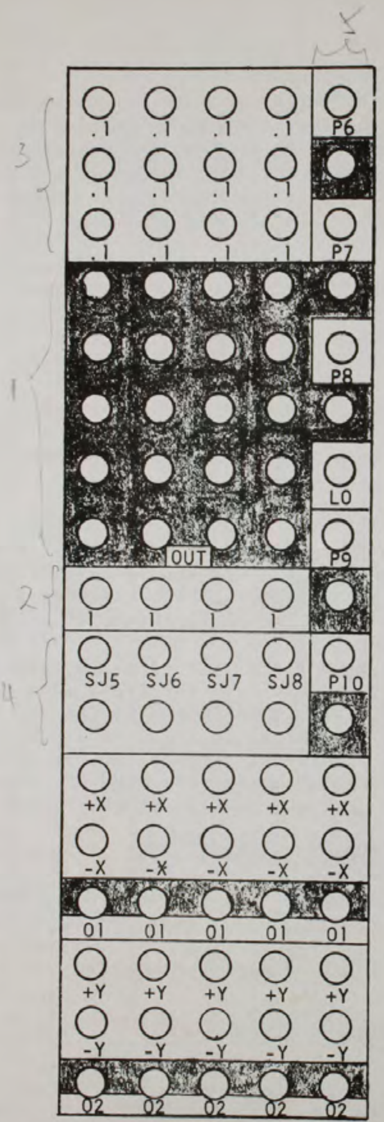


Figure 3-5. Patchboard Layout for 4-Amplifier Multiplier-Summer Area

grounded.

(8) FUNCTION SWITCH CONNECTION. At the bottom of the coefficient-pot panel for pots 1-5 is a lever switch which can be used to apply +100 or -100 volts to the hole marked SW at the lower right corner of the integrator-summer area in Figure 3-3. The switch has a center-off position.

(j) Multiplier-Summer Area

There are 2 multiplier-summer areas, with each area consisting of a 5 x 17 matrix of holes. The area provides connections to summing amplifiers 5 to 8 (each with three 0.1 meg and one 1 meg input resistors), coefficient potentiometers 6 to 10, 4 multipliers and 2 diode function generators.

The multiplier-summer area is illustrated in Figure 3-5, and the actual circuit connections are shown in Figure 3-6. The detailed description follows.

(1) AMPLIFIER OUTPUTS. The 4 x 5 matrix of holes extending from row 4 to row 8 in Figure 3-5 have a black background and are labeled OUT. Columns 1, 2, 3, and 4 provide five output connections to amplifiers 5, 6, 7, and 8, respectively.

(2) 1 MEGOHM INPUT RESISTORS. Directly below the black output holes is a row of 1 meg input resistors with yellow background. Columns 1, 2, 3, and 4 provide a single 1 meg input resistor for amplifiers 5, 6, 7, and 8, respectively.

(3) 0.1 MEGOHM INPUT RESISTORS. The 4 x 3 matrix of holes with white background at the top of the multiplier-summer area provides connections to 0.1 meg input resistors. Columns 1, 2, 3, and 4 provide connections to three 0.1 meg input resistors for amplifiers 5, 6, 7, and 8, respectively.

(4) SUMMING-JUNCTION CONNECTIONS. Directly below the row of yellow 1 meg holes is a 4 x 2 matrix of holes with blue background (rows 10 and 11 in Figure 3-5) labeled SJ5, SJ6, SJ7, and SJ8. Columns 1, 2, 3, and 4 provide two connections to the summing junction of amplifiers 5, 6, 7, and 8, respectively.

(5) COEFFICIENT-POT CONNECTIONS. The top 11 holes of column 5 in Figure 3-5 provide connections to coefficient-pots 6 to 10. The pot input holes have red background and are labeled P6, P7, P8, P9, and P10 for pots 6, 7, 8, 9, and 10, respectively. The output hole for each pot has black background and is located directly below the input hole for that pot. As shown in Figure 3-6

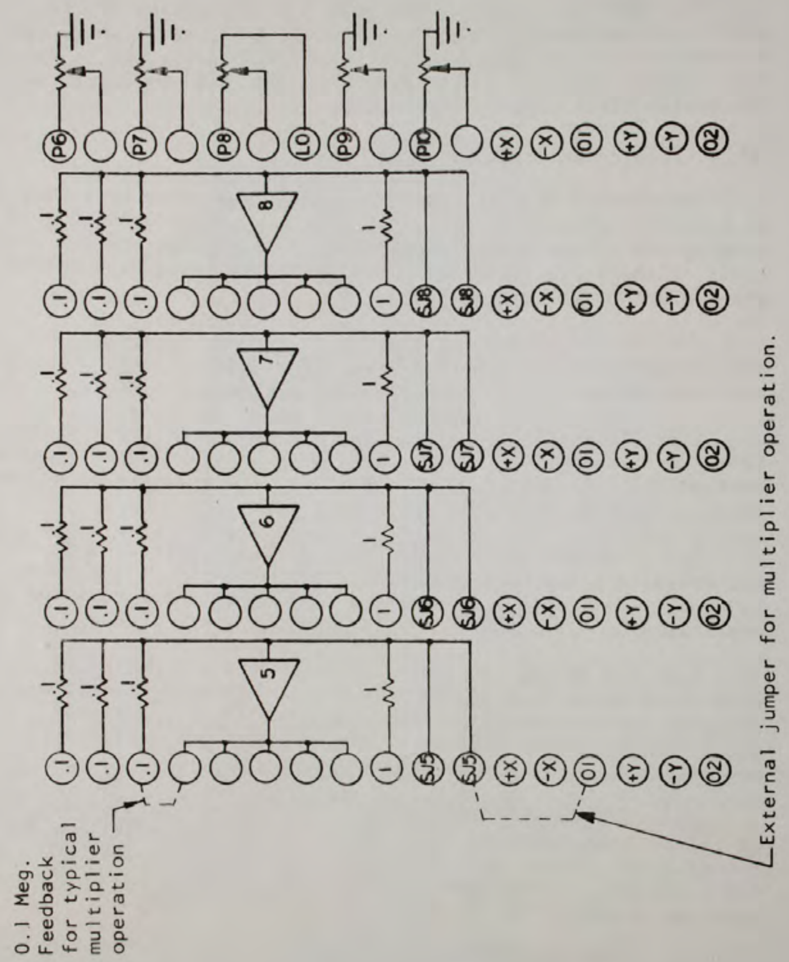


Figure 3-6, Patchboard Circuit Schematic, Multiplier-Summer Area

the input hole for each pot is connected to the high side of the pot, the output hole is connected to the pot wiper arm, and the low side of the pot is grounded, except in the case of pot 8. The low side of pot 8 is connected to the grey hole marked LO directly below the output hole for pot 8. The LO side of pot 8 must be connected to ground with a patchcord if pot 8 is to be used as a conventional coefficient pot.

(6) MULTIPLIER CONNECTIONS. At the bottom of the multiplier-summer area is a 5 x 6 matrix of holes which provide connections to electronic multipliers and diode function generators. In the standard configuration columns 1 to 4 provide connections to four multipliers while column 5 provides connections to two diode function generators. In each multiplier column the top two holes have red background and are labeled +X and -X, respectively. The multiplier inputs +X and -X are patched into these holes. The 3rd and 6th (bottom) holes in each column have black background and are labeled 01 and 02, respectively. Both these holes are connected to the multiplier output and either one must be patched to an amplifier-summing junction to make the output of that amplifier generate the product -XY. With a 0.1 megohm feedback the amplifier output will be -100 volts when X = Y = 100 volts. The 4th and 5th holes in each multiplier column have red background and are labeled +Y and -Y, respectively. The multiplier inputs +Y and -Y are patched into these holes.

(7) DIODE FUNCTION GENERATOR CONNECTIONS. As indicated in the previous paragraph the 5th column of 6 holes at the bottom of the multiplier-summer area is connected to two diode function generators in the standard patchboard configuration. The top two holes in the column have red background and are labeled +X and -X. The voltage inputs to DFG No. 1 (DFG is the abbreviation for diode function generator) are patched into these two holes. The black hole labeled 01 below these two holes is the DFG output and must be patched to the summing junction of an amplifier. The amplifier output voltage will then represent -f(X), the desired function of X. Normally a 1 meg feedback resistor is used with the amplifier. The 3rd and 2nd holes from the bottom of column 5 are colored red and labeled +Y and -Y. The inputs +Y and -Y to DFG No. 2 are patched into these holes. The last hole in column 5 is black and labeled 02, and is patched to an amplifier summing junction. The amplifier output voltage then represents -f(Y).

MUDPAC Manual

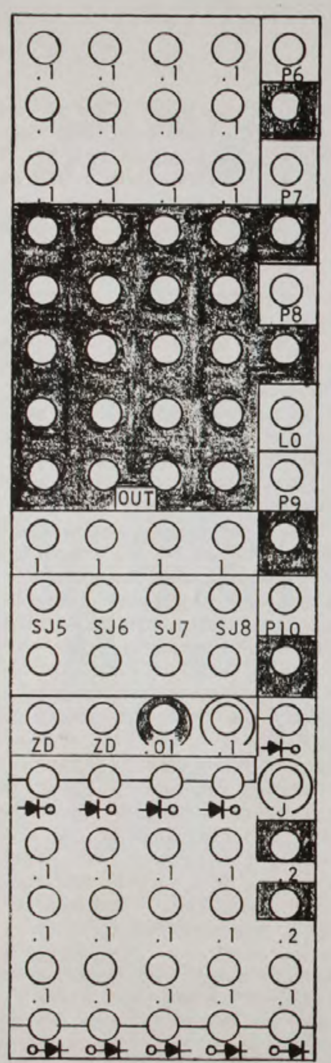


Figure 3-7 . Patchboard Layout for the 4-Amplifier Summer-Diode Area

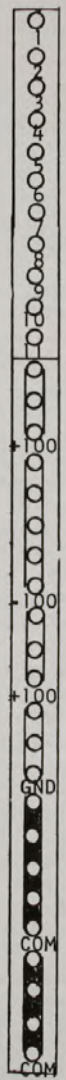


Figure 3-9 . Patchboard Layout for the 34-Hole Column Separating Four-Amplifier Areas

Note that when an amplifier is used to generate the output of a multiplier or DFG, any number of additional inputs can be patched into the amplifier.

(k) Summer-Diode Area

There are 4 summer-diode areas at the bottom of the patchboard with each area consisting of a 5 x 17 matrix of holes. From left to right across the patchboard are multiplier-summer, summer-diode, multiplier-summer, summer-diode areas, etc., alternating. The summer-diode area provides connections to summing amplifiers 5 to 8 (each with three 0.1 meg and one 1 meg input resistors), coefficient pots 6 to 10, and 5 diode networks. The area is illustrated in Figure 3-7 and the circuit schematic is shown in Figure 3-3 . The connections to amplifiers 5 to 8 and pots 6 to 10 are located and labeled identically with the same components in the multiplier-summer are described in the previous section. The details of the diode networks and other components follow.

(1) DIODE NETWORKS. The 5 x 5 matrix of holes at the bottom of the summer-diode area provides connections to the five diode networks the circuits of which are shown in Figure 3-8 . Column 1 provides holes connected to two silicon junction diodes (at top and bottom of the column) and three 0.1 meg resistors, all tied together at a common summing junction. Columns 2, 3, and 4 provide connections to three more such diode networks. Column 5 has an extra hole at the top and provides connections to two diodes (at the top and bottom of the column), two 0.2 meg resistors, and one 0.1 meg resistor, all tied together at a common summing junction. This summing junction is available in column 5 and is the blue-circled hole labeled J and located 5th from the bottom of column 5.

The manner in which the diode networks can be utilized for limiting, switching, and other nonlinear functions is described in the section for the Model 192 Diode Network Card.

(2) ZENER DIODES. The 1st and 2nd holes in row 12 have grey background and are labeled ZD. Each is connected to one terminal of a pair of back-to-back Zener diodes, the other terminal of which is connected to the output of amplifier 5 or 6, respectively, as shown in Figure 3-8 . By patching the ZD hole to the blue SJ hole directly above, the amplifier output will limit at the Zener breakdown voltage of the diodes.

(3) CAPACITORS. The 3rd and 4th holes in row 12 have black and black-and-white circles surrounding them, and are labeled .01

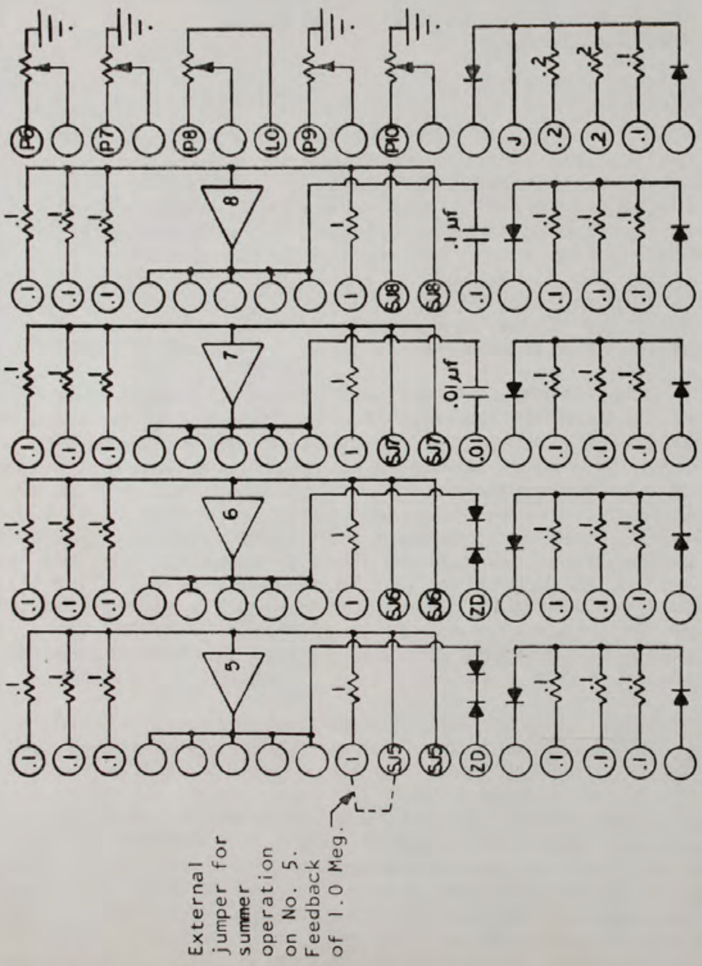


Figure 3-8 , Patchboard Circuit Schematic, Summer-Diode Area.

and .1, respectively. They are connected to 0.01 and 0.1 mfd capacitors, the other terminals of which are connected to the outputs of amplifiers 7 and 8, as shown in Figure 3-8 . Thus the capacitors can be patched as feedbacks around either amplifier. The use of these capacitors in hysteresis, sample-and-hold, and other circuits is described in the section on the Model 192 Diode Network Card.

(1) <u>Miscellaneous Connections</u>

Each of the 5 x 17 hole, four-amplifier areas described in the previous three sections are separated on the patchboard by a single column of holes (see Figure 3-9). The top 11 holes in each of these single columns have grey background and are labeled 1 to 11, respectively. These holes are available for external connections or inter-console trunk connections

A C E and G are the external connection areas for both consoles, whilst areas B, D, F and H provide the inter-console trunking facilities.

The next 3 holes are red and black and provide connections to the +100 volt reference supply. Below these are 5 black and white holes connected to -100 volts, with 3 more red and black holes connected to +100 volts. Below these are 3 blue and white holes connected to signal ground. Finally, at the bottom of the column are a group of 5 holes labeled COM and a second group of 4 holes labeled COM. These provide convenient commons for multiple connections. Normally the computer meter bus is brought out to the extreme upper right hand hole on the patchboard. This facilitates continuous monitoring of an amplifier output on the control-panel meter. However, when this connection is used, <u>other pushbuttons should not be depressed</u> since that would connect several amplifier outputs or pot outputs together.

Depressing a potentiometer pushbutton when another connection is already on the meter bus is the most common cause of a blown potentiometer fuse.

4. Amplifier Monitor Panels

Above the patchboard area in Figure 1-1 can be seen the black amplifier-monitor panels. Each panel contains the output pushbuttons, overload lights, and balance adjust knobs for eight amplifiers. The top panels monitor amplifiers 1 to 4, groups A through H , while the bottom panels monitor amplifiers 1 to 4, groupsA2,B2,C2,and amplifiers 5 to 8, groups D through H.

Figure 5-1, Control Panel

(1) AMPLIFIER OUTPUT PUSHBUTTONS. At the top of each panel are eight pushbuttons, one for each of the eight amplifiers. When any one of these pushbuttons is depressed, it connects the output of that amplifier to the meter input bus, which displays the output of that particular amplifier on the control-panel meter. Thus more than one button should not be depressed simultaneously, since that would connect several amplifier outputs together.

(2) NEON OVERLOAD LIGHTS. Below the eight pushbuttons are eight neon overload lights, which become illuminated when any of the eight corresponding amplifiers become overloaded (output voltage no longer proportional to the input voltages). The neon overload indicators operate whether or not drift-stabilizing amplifiers are used with the manually-balanced dc amplifiers. The neon overload bulbs will frequently glow for amplifiers with no feedback impedance, even when they also have no input. This will occur on OPERATE, RESET, or HOLD and is a perfectly harmless and normal condition. For unused amplifiers in this condition the neon light can be extinguished simply by patching in a feedback resistor.

(3) AMPLIFIER BALANCE ADJUST KNOBS. Below the eight neon overload lights are the knobs for the balance-adjust pots for the eight amplifiers, respectively. To adjust the dc balance, the computer control switch on the control panel is thrown to BAL. CHK. The balance-adjust knobs are then turned until the neon overload light for the corresponding amplifier goes out. For manually-balanced amplifiers on BAL. CHK. the neon bulb goes out when the amplifier offset referred to input is less than about ±2 millivolts. For stabilized amplifiers the figure is about ±200 microvolts.

5. Control Panel

In the upper right corner of Figure 1-1 can be seen the control module. Figure 5-1 shows more detail.

(1) METER. At the top of the control module is the meter which is used to monitor the amplifier outputs, power supply voltages, and as a null-reading device when reading voltage outputs by means of the null pot. This meter is protected against excessive current by diode circuits, so that even if several hundred volts are applied to the meter when it is on the 1 volt scale, it will not damage the meter.

(2) METER SCALE SWITCH. Directly below the meter is a rotary selector switch. The positions marked 1, 10, 100, 500 provide a full-scale meter range of ±1, ±10, ±100, and ±500 volts

respectively. On the -500 and -250 positions the meter reads the output voltage of the -500 and -250 volt power supplies, respectively, with full scale equal to ±500 volts. On the -100 and +100 positions the meter reads the output of the reference-voltage supply, with ±100 volts equal to full scale. In the +200 position the meter reads the output of the +200 volt supply, with ±500 volts full scale. Finally, in the +24 position the meter reads the output of the 24 volt relay supply voltage, with ±100 volts equal to full scale. The circuitry is such that power supply voltages are read independently of -NULL, METER, +NULL switch position.

(3) REFERENCE SUPPLY OVERLOAD LIGHTS. To the left and right of the meter scale switch are two neon lights which are overload indicators for the -100 and +100 volt reference supplies, respectively. Should either of the amplifiers which supply these voltages go out of regulation, the appropoiate neon bulb will light.

(4) METER BUS, EXT. INPUT SWITCH. Below the meter scale switch are two toggle switches. The left switch is labeled METER BUS AND EXT. INPUT. In the up position this switch connects the meter input circuit to the meter bus, so that the output of any amplifier or pot in the computer can be read with the meter by depressing the pushbutton for that particular amplifier or pot. The amplifier output pushbuttons are located along the top of the amplifier modules. The pot pushbuttons are located below each respective pot dial. Note that the pot pushbutton not only connects the pot output to the meter but also connects +100 volts across the pot. Normally the pot pushbutton is used only for null reading of the pot output, i.e., when the meter is a null indicator between the pot output and the null-pot output. <u>If one attempts to read the pot output directly with the meter, a considerable error results from the current drawn by the meter circuit</u>.

In the down position the METER BUS, EXT. INPUT switch connects the meter circuit to the banana jack marked EXTERNAL INPUT at the lower left of the panel. Any voltage in the computer can then be patched to this point and read continuously with the meter.

(5) -NULL, METER, +NULL SWITCH. This switch is located directly below the meter scale switch and is only operative when the meter scale switch is in the 1, 10, 100 or 500 position. In the center position it connects the meter circuit between the meter bus and ground, so that the meter reads directly the voltage appearing on the meter bus. In the left position (-NULL) the switch connects the meter circuit between the meter bus and the null-pot output, and applies -100 volts to the null pot. Thus the meter indicates the difference between the output voltage of the meter bus and the null pot. If the meter bus voltage is negative, this voltage difference can be brought to zero as indicated by

meter null by adjusting the null pot. The digital dial on the null pot then indicates the negative voltage on the meter bus, e.g., an amplifier output voltage obtained by depressing the amplifier output pushbutton. In the right position (+NULL) the switch connects the meter between the meter bus and the null-pot output, and connects +100 volts across the null pot. This allows positive voltage outputs to be read with the digital dial on the null pot, e.g., the voltage output of a pot as obtained by depressing the pot output pushbutton. Note that in the -NULL or +NULL position the meter sensitivity is a maximum and is independent of the position of the meter scale switch. Diode circuits and series lamp circuits prevent more than full-scale needle travel even though the null pot is far away from the null setting. As the null pot comes close to the correct null setting the meter sensitivity increases, and the null pot is easily set to 0.05%. In typical use a voltage is checked in sign and approximate magnitude in the METER position with the meter scale switch in the 100 position. Then the correct null position, +NULL or -NULL, is selected and the null pot is adjusted. The switching circuitry is such that clockwise null pot motion increases meter reading (needle moves to right) independent of the null position, +NULL or -NULL.

(6) NULL POT X.1 AND X.01 SWITCH. To the right of the ±NULL, METER SWITCH is a toggle switch labeled NULL POT. In the up position (X.1) this switch connects ±100 volts to the null pot, depending on whether the meter switch to the left is in the +NULL or -NULL position. Thus the voltage output of the null pot is the null-pot dial reading (0-1000) times one-tenth. In the down position (X.01) this switch connects a resistor in series with the null pot so that only ±10 volts appears across the null pot. Thus the null-pot voltage output is the dial reading times one-hundredth. This allows three-place accuracy in reading voltages below ten volts with the null pot.

(7) DIGITAL NULL-POT DIAL. This dial is located in the lower center of the control panel and allows the null-pot setting to be read to 3 significant figures.

(8) COMPUTER CONTROL SWITCH. Directly below the digital null-pot dial is the computer-control switch which is the switch that controls the operation of the computer. It has four positions: BAL. CHK., RESET, OPERATE, HOLD. In the BAL. CHK. position the switch energizes the balance-check relays in the amplifier modules, which in turn connect each amplifier with a 1,000,000:1 feedback-to-input resistor ratio with the input resistor grounded. The neon overload bulb will light for any amplifier which is more than about ±2 millivolts out of balance referred to input (±200 microvolts for stabilized amplifiers). The amplifiers out of balance

are adjusted using the balance adjust knobs, as explained in Section 4.

In the RESET position the computer control switch energizes the reset relays. This applies initial conditions to all integrators.

In the OPERATE position all relays are released and the integrating amplifiers proceed to integrate their respective input voltages. Thus the problem solution proceeds.

In the HOLD position the hold relays are energized. This disconnects all inputs from integrators and causes the solution to "freeze" in its current condition. At any subsequent time the control switch can be returned to OPERATE, causing the solution to proceed again. Or the switch can be returned to RESET, thus applying once more the initial conditions to the integrators.

(9) METER INPUT JACK. This jack is located at the lower right corner of the control panel and is connected to the input of the meter circuitry. Thus some external voltage-reading device, e.g., a digital voltmeter, can be patched in here to allow direct use of the pushbutton selection of amplifier or pot outputs with the meter bus.

6. POTENTIOMETER PANELS

Figure 1-1 shows two 5-potentiometer panels to either side of the patchboard frame, and there are four 10-potentiometer panels in the potentiometer drawer (Figure 6-1). The L.H. pot panels of the sloping face of the computer are labelled 1-5, and are associated with amplifier groups A2 and B2; R.H. pot panels are associated with amplifier groups G and H, and are labelled 6-10.

(a) Pot Group 1-5

Each Pot Panel consists of a vertical strip of five 10-turn pots with two-speed dials.

Below each pot and to the left is the pushbutton output switch for that pot. When depressed this switch disconnects the high side of the pot from the pot-input jack on the amplifier module panel and connects it to +100 volts. The pushbutton, when depressed, also connects the pot wiper arm (pot output) to the meter bus, so that the pot output can be read using the null pot

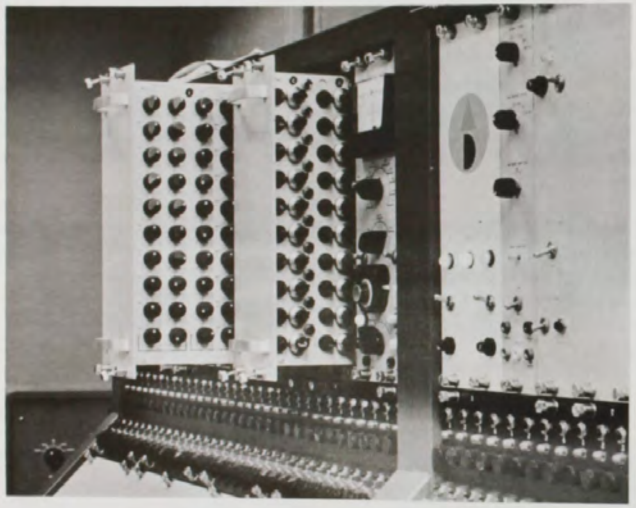


Figure 6-1
Potentiometers and Diode Function Generators in Drawers on Sliding Rails

on the control panel, see Section 5 , parts (5) and (6). Note that the pot output remains connected at all times to the pot-output jack on the amplifier module panel, so that when set against the null pot, the pot is set under load.

At the bottom of the pot panel is a lever switch with positions up, center-off, and down. This single-pole double throw, center-off switch provides a convenient source of ±100 volts at the hole marked SW in the integrator-summer area.

(b) Pot Group 6-10

Each is identical to the Pot Panel described in the previous section except that the pots are numbered 6 to 10 instead of 1 to 5, and there is no lever switch at the bottom of the panel. Also, the low side of pot 8 is not grounded, but is brought out to the hole marked LO in the multiplier-summer or summer-diode area. The low side of pot 8 must be grounded with a patchcord if the pot is to be used as a conventional coefficient pot.

(c) Pot Group 1-10

This Pot Panel contains 10 pots in a vertical strip
It also contains a function switch.

The pot panels in the drawer are associated with amplifier groups C, D, E and F.

If no output voltage is read when a pot set button is pushed, the corresponding fuse should be checked.

If replacement is necessary, be sure to use a 1/32 ampere fuse; larger fuse current ratings will not give protection. Usually, pot fuses are blown when a pot output is inadvertently grounded or connected to an amplifier output.

See also Figure 1-2 for more detail.

7. Power Supply

In Figure 1-1 at the upper left can be seen the power supply panel.

There are two toggle switches on this panel, with three pilot lights above the switches. The left switch controls the ac power input to the computer and should always be turned on first. When the AC ON switch is on, the pilot bulb above this switch (the green bulb on the left side of panel) is illuminated.

Approximately 30 seconds after the AC ON switch is turned on, a thermal time-delay relay within the power supply closes and the amber-colored READY light illuminates. This is the center of the three pilot bulbs. It indicates that the DC ON switch can be thrown up, which energizes the relay connecting the high-voltage transformer secondary to the dc supply rectifiers. Thus the dc voltages (-500, -250, and +200) are turned on. The red DC ON light on the right side of the panel illuminates when the DC switch is thrown on.

The DC voltage switch can be turned off at any time as long as the AC ON switch is left on, the READY light will stay illuminated. This means that the DC voltage can be switched back on at any time. However, if the AC ON switch is turned off, all lights will go out. indicating that both DC and AC power is turned off. It is best to also turn off the DC switch under these conditions, so that if the AC power is turned on again, the time delay relay, if still closed because of insufficient cooling time, will not cause the dc power to go on simultaneously.

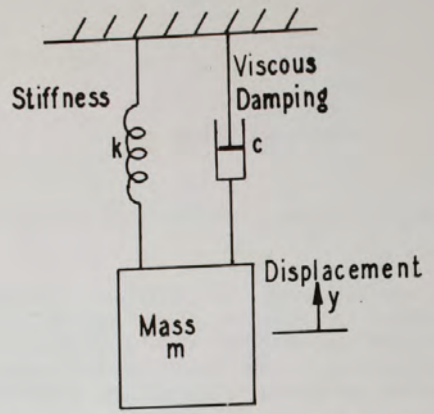


Fig. 8-1. Mass-Spring-Damper Problem.

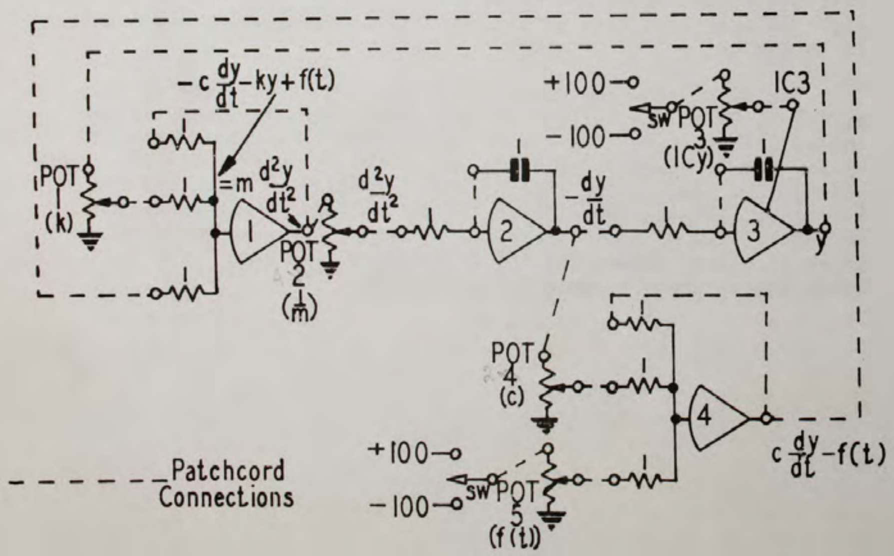


Fig. 8-2. Problem Schematic.

8. A SIMPLE PROBLEM EXAMPLE

As a simple example to show how integrators and summers can be used to solve a problem, consider the mass spring damper system shown in Figure 8-1. Summing vertical forces acting on the mass, we have

$$m \frac{d^2y}{dt^2} + c \frac{dy}{dt} + ky = 0$$

or

$$m \frac{d^2y}{dt^2} = -c \frac{dy}{dt} - ky$$

Here y is the vertical motion of the mass m, c is the viscous damping constant, and k is the spring constant. Assume that the input to pot 4 in Figure 8-2 is a voltage representing m d^2y/dt^2. If we set pot 4 at 1/m, then the output voltage of pot 4 will be d^2y/dt^2. This is fed into amplifier 2 through a one megohm input resistor. Since this amplifier also has a one microfarad feedback capacitor, the RC time constant for the integrator is $10^6 \times 10^{-6} = 1$ second, and the amplifier output voltage is the time integral of the input voltage, with a sign reversal, i.e., -dy/dt. This voltage is patched into amplifier 3, which also has a one megohm input resistor and a one microfarad feedback capacitor. Thus the output of amplifier 3 is $-\int (dy/dt)\, dt = y$. This voltage is patched into pot 1, which is set at k. The resulting voltage ky is patched into amplifier 1 through a one meg input. With a one meg feedback this produces a voltage -ky at the output of amplifier 1.

The voltage output -dy/dt of amplifier 2 is then inverted in amplifier 4 and patched into pot 2, which is set at c. The resulting voltage c dy/dt is fed into amplifier 1 through a one meg input, producing a voltage -c dy/dt at the output of amplifier 1. Thus the total output voltage of amplifier 1 is -c dy/dt -ky, which, according to the Equation , should equal m d^2y/dt^2. It is made so by patching the output of amplifier 1 into pot 4. The electronic differential analyzer circuit for solving this problem is now complete. The settings on pots 1, 2, and 4 represent, respectively, k, c, and 1/m. For coefficients larger than 1, the pots are set at 1/10 the coefficient value and the pot output is fed into the next amplifier through a 0.1 meg resistor. For coefficient values larger than 10 or smaller than 1/10 the circuit should, in general, be rescaled. This technique will not be considered here.

To complete the problem statement we must specify the initial conditions on the displacement y and velocity dy/dt of the mass. Let us assume that initially

$$y(0) = 100 \text{ volts}$$

$$\frac{dy}{dt}(0) = 0$$

Since the output of amplifier 2 represents -dy/dt, which is initially zero, we do not need to patch an initial condition voltage into this amplifier. The initial condition of +100 volts on amplifier 3 is established by patching -100 volts into the IC hole for amplifier 3. When the computer control switch on the control panel is turned to RESET, this should cause the output of amplifier 3 to be +100 volts.

When the control switch is turned to OPERATE, the initial conditions are released and the solution to the mass spring damper problem begins. For c = 0 (no damping) this solution will simply be undamped sinusoidal oscillations of frequency $\sqrt{k/m}$. As c is increased for each successive solution, the oscillations will damp more and more. When $c = 2\sqrt{mk}$ the solution is critically damped, barely failing to overshoot. For larger values of c the solution is overdamped (exponential) in nature.

Consider in addition the application of an external force to the mass, so that the equation of motion becomes

$$m\frac{d^2y}{dt^2} = -c\frac{dy}{dt} - ky + f(t)$$

We will assume a zero initial condition on y and dy/dt.

The solution schematic, Figure 8-2, has been completed to include f(t) by inclusion of pot 5 which provides a step input for this function. The actual computer diagram is shown in Figure 8-3, where the usual symbols have been used.

The circuit of Figure 8-3 is set up and operated as follows on the computer, using any of the integrator-summer areas, say area A2.

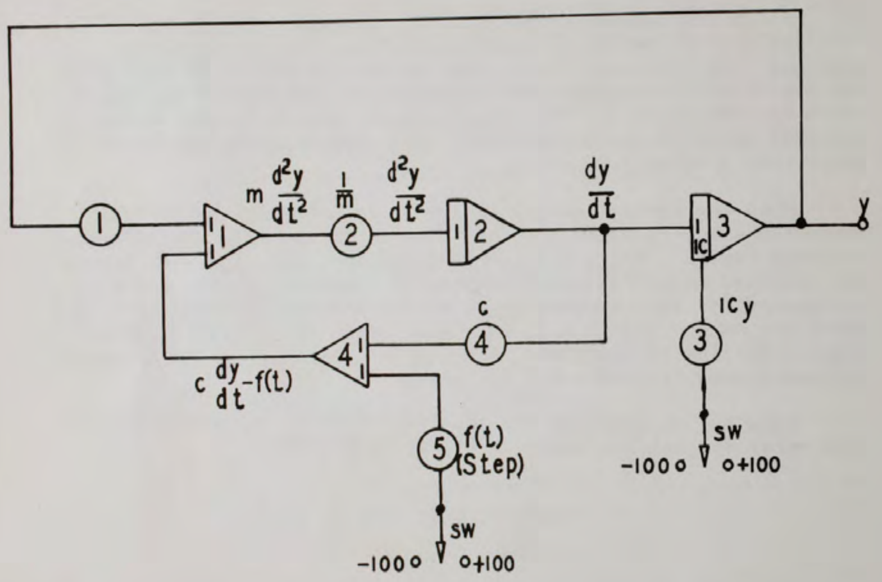


Fig. 8-3. Problem, Computer Diagram.

(1) Connect amplifier 2 as an integrator by patching a red cord from the hole G2 (top hole in column 2) to the blue 12 hole directly to the left. Connect a 1 mfd feedback capacitor to amplifier 2 by patching a red cord from the hole labeled 12 in column 5 (2nd hole from the top) to the yellow hole labeled 1 directly below.

(2) Connect amplifier 3 as an integrator by patching an red cord from the hole G3 (top hole in column 3) to the blue 13 hole directly to the right. Connect a 1 mfd feedback capacitor across amplifier 3 by patching a red cord from the hole labeled 13 in column 5 (5th hole from the top) to the yellow hole labeled 1 directly below.

(3) Patch a 1 meg feedback around amplifier 1 with a red cord from lowest black output hole for amplifier 1 (hole 12 in column 1) to the yellow 1 meg hole directly below.

(4) Patch a 1 meg feedback around amplifier 4 with a red cord from the lowest black output hole for amplifier 4 (hole 12 in column 4) to the yellow 1 meg hole directly below.

(5) Patch from the output of amplifier 1 to the input of pot 2. Use a red cord from the third black output hole in column 1 (9th hole from the top) to the red input hole labeled P2 in column 5.

(6) Patch the output of pot 2 into a 1 meg input resistor of amplifier 2. Use a red cord from the black output hole of pot 2 (hole 10 in column 5) to the top yellow 1 meg hole for amplifier 2 (hole 13 in column 2).

(7) Patch from the output of amplifier 2 into a 1 meg input resistor of amplifier 3. Use a red cord from the lowest black output hole for amplifier 2 (hole 12 in column 2) to the yellow 1 meg hole directly below and to the right (hole 13 in column 3).

(8) Patch the output of amplifier 3 to the input of pot 1. Use a red cord from the top black output hole of amplifier 3 (hole 7 in column 3) to the red input hole labeled P1 in column 5.

(9) Patch the output of pot 1 into a 1 meg input resistor for amplifier 1. Use a red cord from the black output hole of pot 1 (hole 8 in column 5) to the second yellow 1 meg hole for amplifier 1 (hole 14 in column 1).

(10) Connect the output of amplifier 2 to the input of pot 4. Use a red cord from the next to lowest black output hole for amplifier 2 (hole 11 in column 2) to the red input hole labeled P4 in column 5.

(11) Connect the output of pot 4 to a 1 meg input resistor for amplifier 4. Use a red cord from the black output hole of pot 4 (hole 14 in column 5) to the yellow 1 meg hole directly to the left.

(12) Connect the output of amplifier 4 to a 1 meg input resistor for amplifier 1. Use a red cord from the next to lowest black output hole for amplifier 4 (hole 11, column 4) to the third yellow 1 meg input hole for amplifier 1 (hole 15 in column 1).

(13) We will use the function switch to provide ±100 volts to pot 5, thereby producing step-voltage inputs to amplifier 4. Patch a red cord from the grey hole labeled SW (hole 17 in column 5) to the red input hole labeled P5 which is two holes above.

(14) Patch the output of pot 5 to a 1 meg input resistor for amplifier 4. Use a red cord from the black output hole for pot 5 (hole 16 in column 5) to the yellow 1 meg hole directly to the left.

(15) Next we will patch in the initial condition pot, although we will not actually use it in the example problem here, since we will start with zero initial conditions. Patch a red cord from the black output hole of pot 3 (hole 12 in column 5) to the grey hole labeled IC3 in column 3 (17th hole from the top of column 3). Now either +100 volts or -100 volts can be patched into pot 3, depending on whether a negative or positive initial condition on amplifier 3 is desired. By adjusting pot 3 with the computer on RESET, the output of amplifier 3 can be nulled against the null pot setting which represents the desired initial conditions. As stated earlier, we will let the initial conditions be zero for the example here.

(16) For an example solution set pots 1 and 2 at unity (full scale) so that k = m = 1. Set pot 4 at zero (c = 0). Set pot 5 at approximately 0.5 (half of full scale). This should provide ±50 volts input representing f(t) when the function switch is thrown up or down.

(17) Set the computer to RESET with the computer control switch at the bottom of the control panel. To monitor the displacement y continuously, connect the METER BUS, EXT. INPUT switch to METER BUS and patch from a black output hole of amplifier 3 to the extreme upper right hole of the patchboard.

(18) Set the meter on the 100 scale. Set the function switch in the center position. Turn the control switch from RESET to OPERATE. Since there are no initial conditions and $f(t) = 0$, the output y of amplifier 3 will stay zero. Next deflect the function switch UP. This applies a step input of +50 volts and the displacement should begin to oscillate sinusoidally between +100 and zero volts. The frequency of oscillation will be $\sqrt{k/m} = 1$ radian/second, i.e., a period of $2\pi = 6.28$ seconds.

(19) Repeat (18) with increasing amounts of viscous damping c, as set on pot 4. For pot 4 at full scale ($c = 1$) the damping will be 0.5 of critical, and the oscillation should exhibit about a 17% (8.5 volt) overshoot. To set higher amounts of damping a 0.1 meg input resistor must be used with pot 4. Since this gives amplifier 4 a gain of 10 for the input voltage from pot 4, that voltage must be $-0.1\ c\ dy/dt$, or pot 4 should be set at c/10, and values of c up to 10 can be set. In general the damping ratio $\xi = c/2\sqrt{mk}$; $\xi = 1$ for critical damping.

(20) Next change the 1 mfd feedback capacitors for amplifier 2 and 3 to 0.1 mfd. To make this change unplug the red patchcord from the yellow 1 mfd hole for amplifier 2 (3rd hole from the top, column 5) and reconnect it to the black and white 0.1 mfd hole for amplifier 2 (the top hole in column 5). This connects the blue I2 terminal (2nd hole from the top, column 5) to the 0.1 mfd capacitor for amplifier 2. Similarly, unplug the red patchcord from the yellow 1 mfd hole for amplifier 3 (6th hole from the top, column 6) and reconnect it to the black and white 0.1 mfd hole for amplifier 3 (the 4th hole from the top, column 5). This connects the blue I3 terminal (5th hole from the top, column 5) to the 0.1 mfd capacitor for amplifier 3.

(21) Repeat (18) and (19). Since the integrators now have 0.1 second time constants instead of 1 second time constants, the problem solution proceeds at exactly ten times the previous speed. The same effect can be obtained by leaving the capacitors at 1 mfd but changing the input resistors for amplifier 2 and 3 from 1 meg to 0.1 meg.

Various types of input functions f(t) other than step functions can be generated. A constant velocity (ramp function) input can be obtained by patching a step function into one of the other integrators. Its output then becomes f(t) when the control switch is thrown to OPERATE. Sinusoidal inputs f(t) can be generated by a circuit similar to that in Figure 8-2 but with no viscous damping constant c.

Note that in patching up the circuit of Figure 8-3 we have attempted to select input and output holes so that whenever possible, the patch cord connection is between adjacent holes. The result is a much cleaner patchboard after all patch cords are in place.

9. Example of Static Check

Consider the problem of the previous section as patched according to the instructions (1) - (11). For purposes of illustration, assume k = 0.732, 1/m = 0.276, c = 0.421, f(t) = 50 volts. Then pots 1, 2, 4, and 5 should, respectively, be set at 0.732, 0.276, 0.421, and 0.500. Leave the function switch UP to apply +100 volts to pot 5. Set the pots against the null pot according to the instructions in Section 5.

Let us now proceed to make a static check of our circuit. To do this we will apply known initial conditions to all integrators (two in this case) and then will check the output of each summer while the computer is on RESET to see whether they agree with the static values they should have. Let the test initial conditions in this case correspond to y(0) = +100 volts, $\frac{dy(0)}{dt}$ = -100 volts. Thus the initial conditions on amplifiers 3 and 2 will be +100 volts and +100 volts, respectively. These are applied by patching -100 volts from the black and white -100 holes in column 6 to the grey IC2 and IC3 holes below the yellow 1 meg holes in columns 2 and 3 are, indeed, both +100 volts.

Now let us calculate what the output of amplifier 4 should be. Since the output of amplifier 4 represents c $\frac{dy}{dt}$ -f(t), it should be 0.421(-100)-50 =-92.1 volts. Next read the output of amplifier 4 with the null pot, as described in Section 5. Within the accuracy of the pot settings the output should be -92.1 volts. Similarly the output of amplifier 1 should be

$$-ky - c\,\frac{dy}{dt} + f(t) = -(0.732)\ 100 + (0.421)(-100) + 50 = 18.9 \text{ volts.}$$

Again the output of amplifier 1, as read with the null pot, should be 18.9 volts.

Finally, let us check the input circuit for amplifier 2. Since this is an integrator, the output voltage will not depend on the input voltage, but rather on the initial conditions.

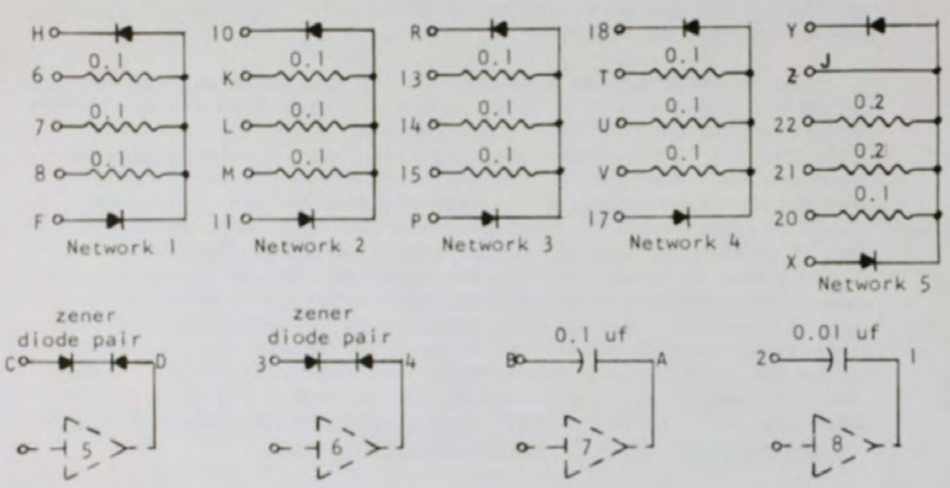
To test the input circuit connect the summing junction SJ2 to the summing junction of an unused summing amplifier in another area. If area A were used for the problem up to this time, then the new summing amplifier could be 1B, i.e., amplifier 1 in area B. Thus a red cord is patched from SJ2 in area A to SJ1 in area B. A 1 meg feedback must also be patched around amplifier 1B (an red cord from a black output hole in column 1B to a yellow 1 meg input hole directly below). The output of amplifier 1B should be the negative of the output of amplifier 1A times 1/m, i.e., -18.9(0.276) = -5.2 volts. This can be checked as before with the null pot. Note that the initial condition of amplifier 2A remains at +100 volts. After this check is made you must remove the patch-cord from SJ2 in area A to SJ1 in area B.

Although the example problem given here is simple enough so that a static check is probably unnecessary, this is not true in larger problems, and the static check is a powerful tool which will locate almost all sources of error in patching up a complicated problem.

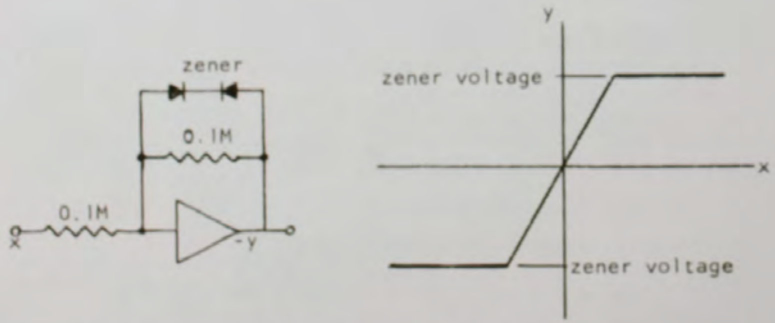
10. General Remarks Concerning the Setting of Coefficient Pots

As described in Section 5 , paragraph (5), the coefficient pots are set under load by means of the Null-Pot on the Control Panel. With the -NULL, METER, +NULL switch on the control panel set in the +NULL position, the pot-output pushbutton next to the pot being set is depressed, which disconnects the input voltage applied to that pot on the patchboard and reconnects the pot input to +100 volts. The meter on the control panel then indicates any unbalance between the pot being set and the Null-Pot, and the pot being set can be varied until meter null indicates it is exactly the same as the Null-Pot setting.

It is important to note that during the above pot-setting procedure the pot output (arm) remains connected to the patchboard and hence to the amplifier input resistor which it is driving. Thus the pot is set under the resistive load it will be driving the problem. However, if the amplifier which the pot is driving has a gain greater than unity (say 10) and the pot setting is large enough (say 0.5), then when +100 volts is applied to the pot by depressing the pot output button, the amplifier will overload, since it cannot furnish the required -500 volt output. This means that the amplifier summing junction will no longer be at ground potential and the pot-load will be incorrect. However, this effect can be eliminated by setting the pot when the computer is on BAL. CHK., since the summing junction of the input resistors for each amplifier is grounded by the balance check relay contacts when the relay is energized. <u>Thus coefficient pots should always be set with the computer in the BAL. CHK. mode</u>.



FigureII-1. Circuit Schematic for Components on Model 192 Diode Network Card



FigureII-2. Use of Zener Diodes for Voltage Limiting

II. DIODE NETWORKS

General Description

The Model 192 Diode-Network Card contains five special diode networks, two pairs of back-to-back Zener diodes for voltage limiting, one 0.1 mfd polystyrene capacitor, and one 0.01 mfd polystyrene capacitor. It is used to provide capability for programming various functions, such as limiting, hysteresis, square-wave generation, sample and hold, etc.

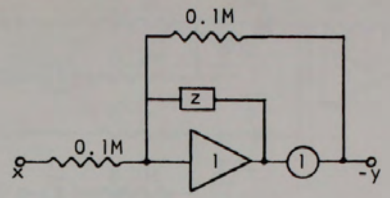
The circuit schematic for the diode networks, the Zener diodes, and the capacitors is shown in FigureII-1. Diode networks 1 to 4 are identical and consist of three 0.1 megohm resistors and two silicon junction diodes connected to a common summing junction. The diode terminals and the 0.1 megohm resistor terminals are available on the patchboard, whereas the summing junction is not. Network 5 has two 0.2 megohm resistors replacing two of the 0.1 megohm resistors and has the summing junction available on the patchboard in addition to the other terminals. The first back-to-back Zener diode pair has one terminal wired to the output of summing amplifier 5 when the card is plugged in place. By patching the other terminal to the amplifier summing junction, the amplifier output voltage limits at the Zener breakdown voltage of the diodes. Similarly, the second back-to-back Zener diode pair is wired to amplifier 6. The 0.01 mfd capacitor has one terminal wired to the output of amplifier 7. By patching the other terminal to the amplifier summing junction, the capacitor becomes a 0.01 mfd feedback for the amplifier. Similarly, the 0.1 mfd capacitor is wired to amplifier 8.

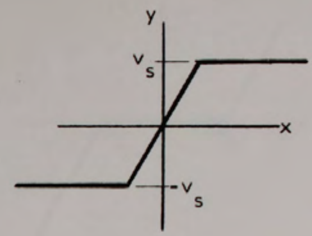
Back-to-back matched Zener diodes form a convenient way to limit amplifier output voltage, as shown in Figure 2-3. This provides nearly ideal voltage limiting (typical deviation is several tenths of a volt over the saturating region). High frequency noise introduced by the diodes when conducting can cause difficulty in this circuitry.

Summary of Nonlinear Circuits

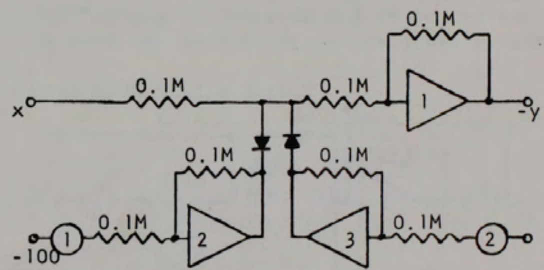
Given below are a number of circuits which utilize silicon junction diodes or Zener diodes. The operation of these circuits is in general self-explanatory. All of them can be conveniently patched using the patchboard connections to the Model 192 Diode Network Card. Note that the symbol $-\boxed{Z}-$ represents two back-to-back Zener diodes.

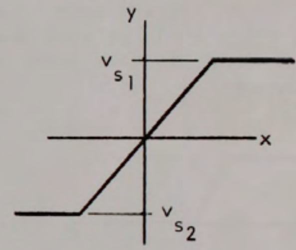
Limiting Circuits





Gain is unity. Saturation level $\pm v_s$ is varied by adjusting Pot 1.

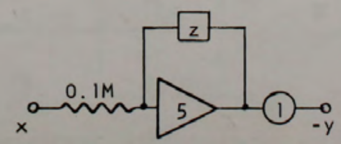


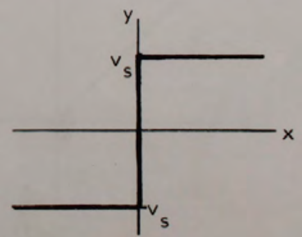


Required: 2 diode networks, 3 amplifiers (amplifier 1 can be used to sum other inputs).

Gain is 0.5 (unless 0.2 meg feedback resistor is used). Amplifier 1 can be used to sum other voltages. Pot 1 adjusts v_{s1}, Pot 2 adjusts v_{s2}. Output of amplifiers 2 and 3 can be replaced by potentiometer outputs, but limiting is soft due to finite pot output impedance.

Bang-Bang Circuit

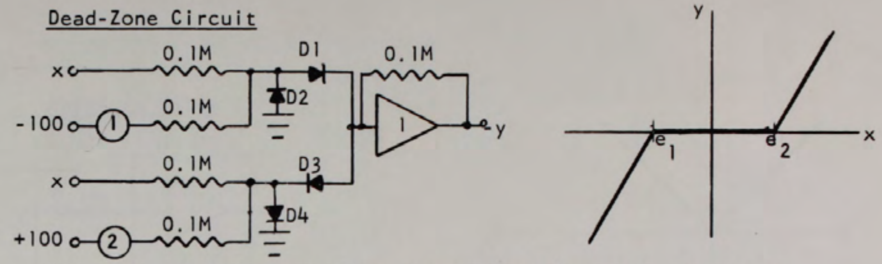




Required: 1 Zener diode pair, 1 amplifier.

Pot 1 adjusts the output magnitude $\pm v_s$.

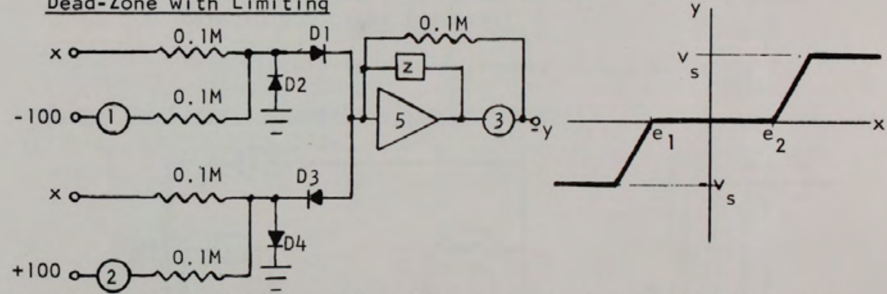
Dead-Zone Circuit



Required: 2 diode networks, 1 amplifier (amplifier 1 can be used to sum other inputs).

Pot 1 adjusts e_1, pot 2 adjusts e_2. Note the use of the "catcher" diodes D2 and D4 to prevent back biasing of D1 and D3 when not conducting. This greatly speeds diode recovery time.

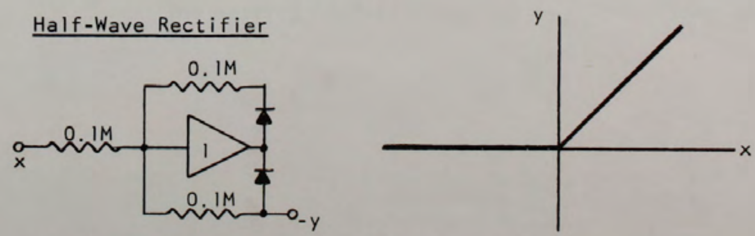
Dead-Zone with Limiting



Required: 2 diode networks, 1 Zener-diode pair, 1 amplifier.

Pot 1 adjusts e_1, pot 2 adjusts e_2, pot 3 adjusts $\pm v_s$.

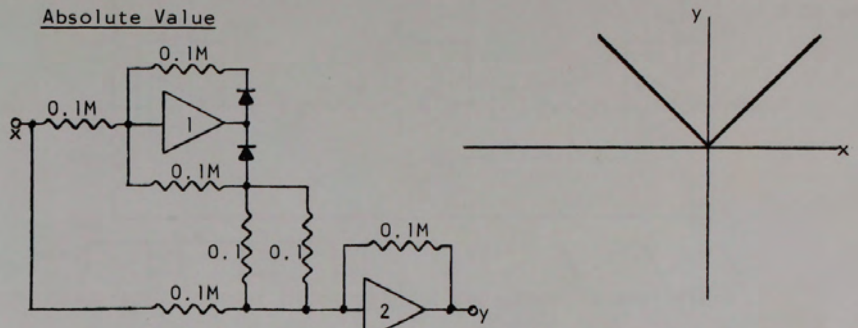
Half-Wave Rectifier



Required: 1 diode network (#5), 1 amplifier

This circuit is extremely accurate.

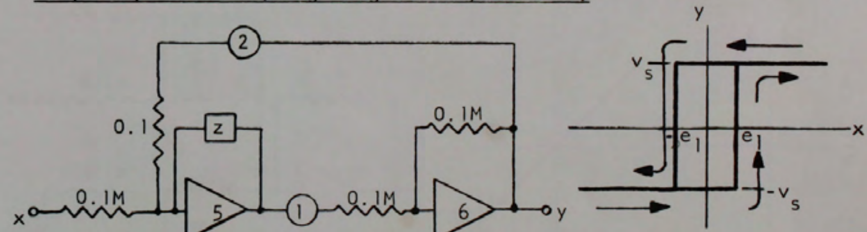
Absolute Value



Required: 1 diode network (#5), 2 amplifiers (amplifier 2 can be used to sum other inputs).

This circuit is also extremely accurate.

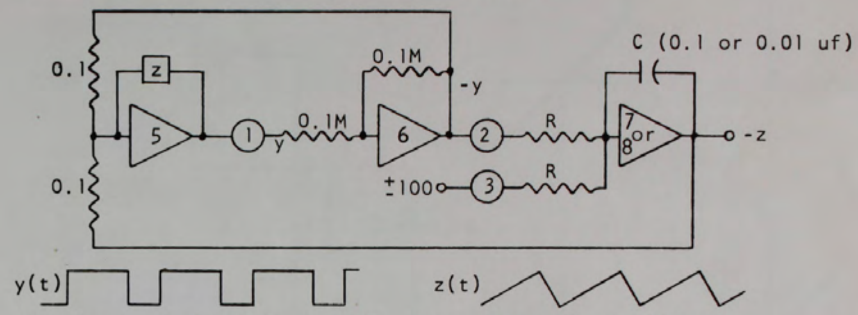
Flip-Flop Circuit (Bang-Bang with Hysteresis)



Required: 1 Zener diode pair, 2 amplifiers.

The setting of Pot 1 controls $\pm v_s$. Pot 2 then adjusts $\pm e_1$.

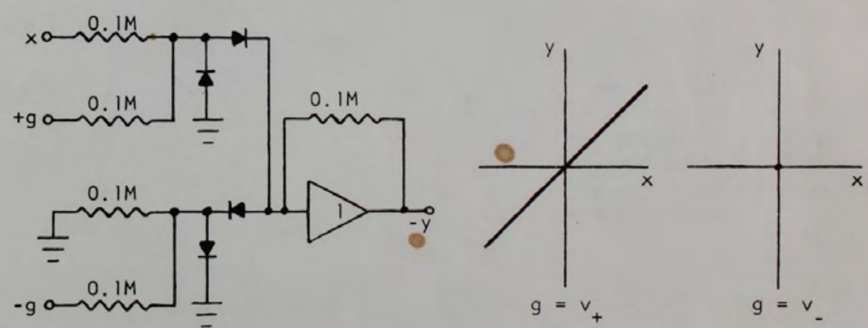
Square Wave and Triangular Wave Generator



Required: 1 Zener diode pair, 1 capacitor, 3 amplifiers.

Pot 1 adjusts the amplitude, pot 2 the frequency, Pot 3 the duty cycle.

On-Off Gate

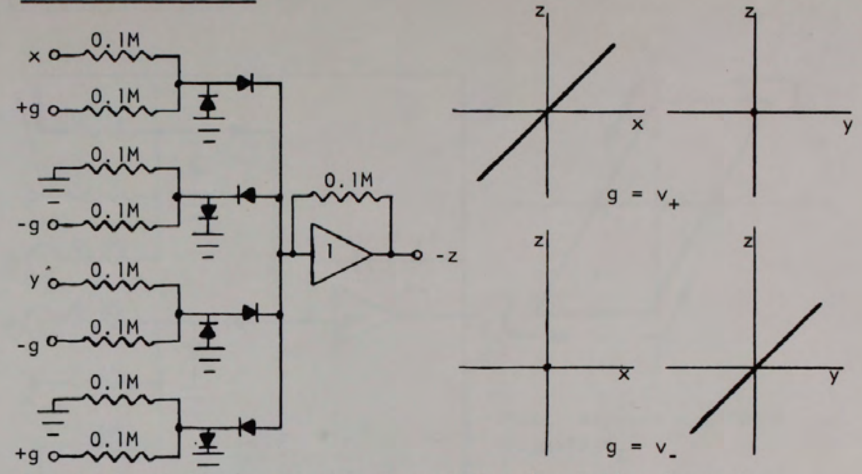


Required: 2 diode networks, 1 amplifier (amplifier 1 can also be used to sum other inputs).

The gate signal g can be derived from a bang-bang circuit such as is shown earlier. A precision inverter yields -g. For switching of x signals ranging from -100 to +100 volts, the magnitude of g should be greater than 100 volts, say ±120 volts. Note that the exact magnitude of g is not important, as long as the -g input is precisely the negative of the +g input, as insured by a precision inverter to obtain -g from +g.

MUDPAC Manual

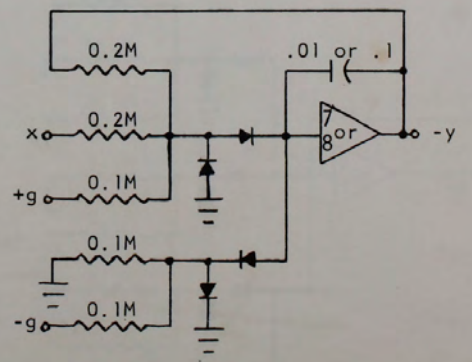
Two-Position Switch



Required: 4 diode networks, 1 amplifier (amplifier 1 can be used to sum other inputs).

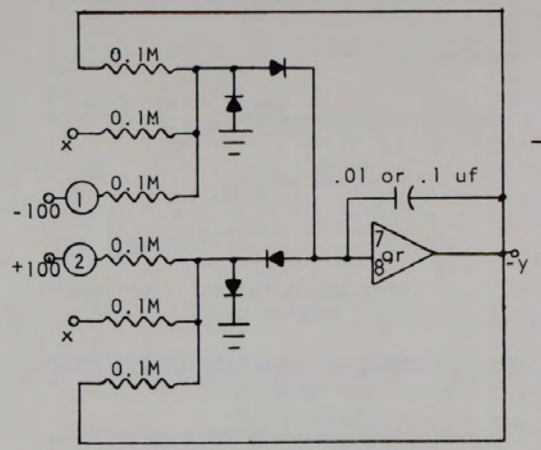
Sample and Hold Circuit

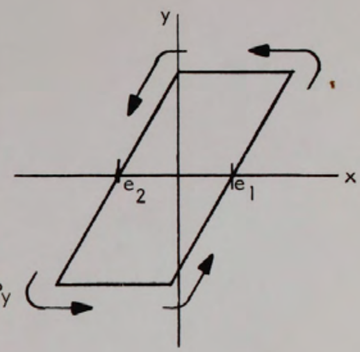
For g = v_+, y = x (.02 or .002 sec time constant). For g = v_-, y holds previous x value.



Required: 2 diode networks, 1 capacitor, 1 amplifier.

Hysteresis Circuit

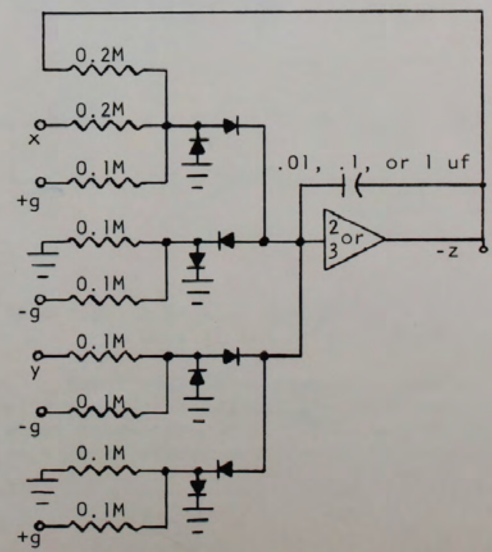




Pot 1 adjusts e_1, Pot 2 adjusts e_2.

Required: 2 diode networks,
1 capacitor,
1 amplifier.

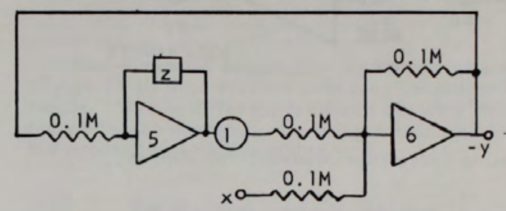
Reset or Integrate Circuit

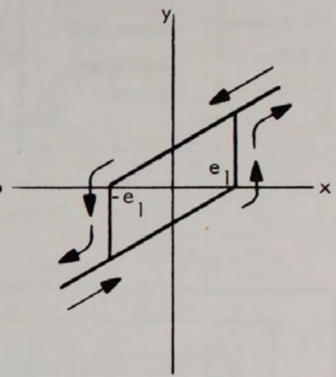


For $g = v_+$, $z = x$ (.002, .02, or .2 sec time constant).
For $g = v_-$, $Z = \frac{1}{RC}\int y\,dt$
(RC = .001, .01, .1 sec).

Required: 4 diode networks,
1 capacitor,
1 amplifier.

Negative Deficiency (Overlap)

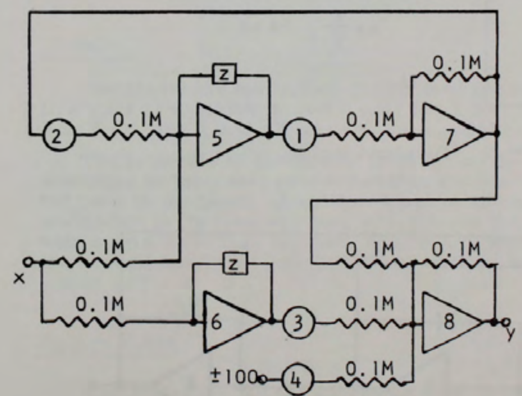


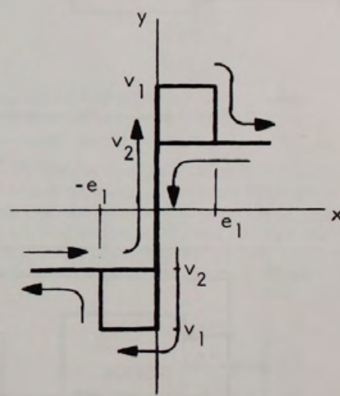


Pot 1 adjusts $\pm e_1$.

Required: 1 Zener diode pair
2 amplifiers

Combined Starting and Coulomb Friction





Required: 2 Zener diode pairs, 4 amplifiers (amplifier 8 can be used to sum other inputs).

Pot 1 adjusts $v_1 - v_2$, Pot 2 adjusts $\pm e_1$, Pot 3 adjusts $v_1 + v_2$. Pot 4 adjusts the magnitude of y for $x > e_1$ to be equal to -y for $x < -e_1$. This may be necessary if the back-to-back Zener diodes are not perfectly matched.

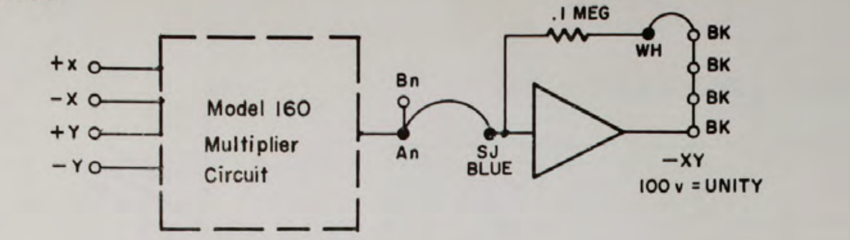


Figure 12-1. Operating Circuit for Model 160 Multiplier.

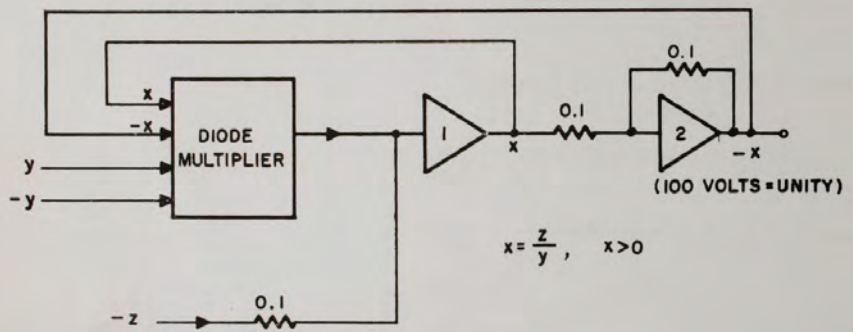


Figure 12-2. Divider Circuit.

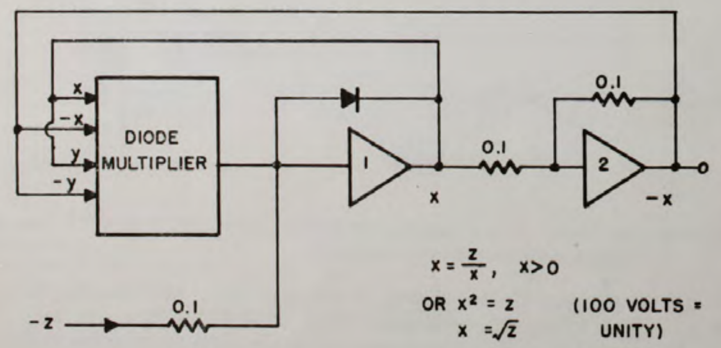


Figure 12 3. Square-Root Circuit.

12. MULTIPLIERS

The method of connecting the Model 160 multiplier for operation is shown in Figure 12-1. Note that the summing amplifier can be used to sum any other inputs. With a different feedback resistor the multiplier gain at the amplifier output can be changed. By using a feedback capacitor instead of a resistor the product can be integrated.

The standard feedback resistor is 100,000 ohms, and other inputs must be through a similar valued resistor to have a through gain of unity. Similarly 1 megohm input resistors will sum these other inputs with a gain of 0.1.

A 1 megohm feedback resistor may be used to provide a multiplier gain of 10.

A feedback capacitor of 1 microfarad will provide a product integrator of gain 10, and 0.1 microfarad a product integrator of gain 100.

Division

The Model 160 multiplier can be used for division with the circuit shown in Figure 12-2, which is useful only for $Y > 0$, where divider output $X = Z/Y$. For $Y < 0$, the X and -X leads to the multiplier must be reversed.

The principle of the circuit is based on the fact that the gain of a feedback amplifier is inversely proportional to the fractional amount of output voltage fed back to the input. Amplifier 1 can be thought of as an amplifier with a multiplier in its feedback loop which feeds the output voltage X back to the input with a gain Y (voltage fed back equals XY, where 100 volts equals unity). Thus the overall amplifier gain is $1/Y$ and with an input voltage -Z it produces an output $Z/Y = X$.

Square Roots

The Model 160 Multiplier can be used to take square roots with the circuit shown in Figure 12-3. This is similar to the divider circuit of Figure 12-2, except that the amplifier outputs $\pm X$ are connected to both the $\pm X$ and +Y multiplier input terminals. For $X > 0$ the output $X = Z/X$, or $X^2 = Z$ and $X = \sqrt{Z}$. Note the diode across amplifier 1 in the figure. This only allows the amplifier output voltage X to take on positive values, and should the input Z become negative for any reason, it prevents the circuit from "hanging" up with a negative output voltage X due to the resulting positive feedback.

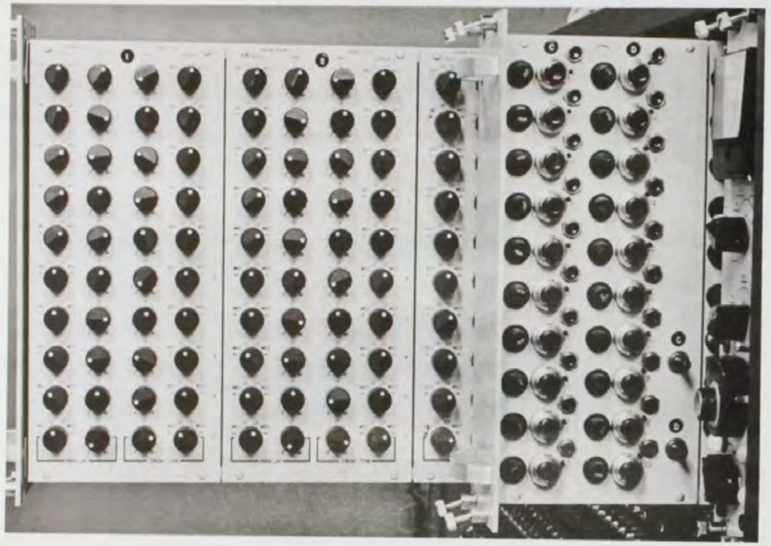


Figure 13-1
Three Model 171 Diode Function Generators Installed in Drawer

13. DIODE FUNCTION GENERATORS

The Model 171 Diode Function Generator is used to simulate any arbitrary function of voltage bv means of 9 straight-line segments in addition to a constant and a linear term. Each Function Generator is mounted on a 5 1/2" x 13" panel.

Three such panels are mounted in a single 4 1/2" x 14" module, as shown in Figure 13-1. The module is pulled out of the computer cabinet on rails in order to expose the function generator panels and allow setting the break-points and slopes.

A detailed illustration of one Function Generator Panel is shown in Figure 13-2.

Function Set-Up Procedure

To set up a function f(X), voltage inputs +X and -X are patched to the function generator input jacks on the patch board. The function generator output is then patched to an amplifier summing junction. Normally a 1 megohm feedback resistor is used with the amplifier, although higher or lower amplifier gains may be used, depending on slope requirements for f(X).

Next a straight-line fit to f(X) which passes through f(0) and matches the slope f'(0) is estimated and the positions of the 9 breakpoints are determined. Fewer breakpoints may be used if desired; to obtain more break points, an additional diode function generator must be paralleled with the first.

All amplitude controls should now be set to zero, including the linear term. This is accomplished quickly by setting the coarse amplitude control to L, and the fine control to zero (counter clockwise). With X = 0, the parallax control is adjusted so that the output of the function generator amplifier is -f(0) volts, as read by the null pot on the control panel. Use the coarse parallax adjust switch to change range as necessary for this setting.

Next set X = +100 volts and vary the linear-adjust control until the amplifier output reads $-f_0(100)$, where f_0 is the straight line fit to f(X) as determined earlier. If this saturates the DFG (diode function generator) output amplifier, then choose a lower value of X, say X = +50, and match to $-f_0(50)$. Or, in some cases, it may be better to match $-f_0(-100)$, i.e., let X be negative, depending on the sign of the parallax bias term set earlier.

The constant and linear portion of f(X) have now been set. Next set $X = X_1$, the first positive break point, by reading X_1 accurately with the null pot. Then read the output of the DFG amplifier with the null pot. Keeping the null pot on this setting, turn the amplitude of segment one to its maximum setting, without worrying about sign as yet. Then vary the break point for segment one until the null on the meter indicates just slightly off zero, say 0.1 volt. The first segment break point e_b has now been adjusted to X_1. Next change X to X_2, the second positive break point, as read accurately by the null pot. Now set $-f(X_2)$ on the null pot and vary the amplitude of segment one until null is achieved, changing sign on the amplitude, if necessary. The function f(X) has now been matched at X = 0, X_1, and X_2 using the parallax, linear-term, and first segment.

Figure 13-2, Model 171 Diode Function Generator, Front Panel

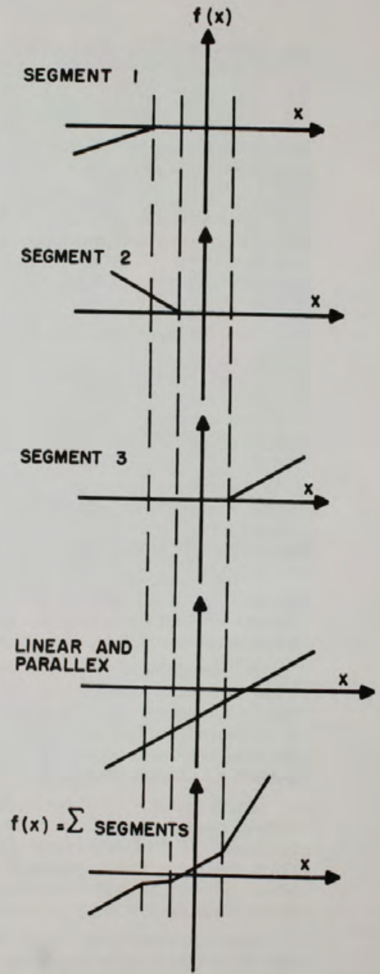


Figure 13-3. Segmented Straight-Line Representation of a Function as the Sum of Individual Segments.

Leaving the null pot at $-f(X_2)$, turn the amplitude of segment two to its maximum value. Then adjust the break point for segment two until the null meter indicates slightly off zero. Next set $X = X_3$ and the null meter to $-f(X_3)$. The amplitude of segment two is adjusted until the DFG output amplifier reads $-f(X_3)$. With $X = X_3$ the break point of segment three is then set, as above, and with $X = X_4$ the amplitude of segment three is adjusted until the DFG output amplifier reads $-f(X_4)$. The procedure continuous in this way until all the segments with positive break points have been set.

Then starting with $X = X_1'$, the first negative break point, and working towards increasingly negative X values, the break points and amplitudes for segments with negative break points are set, using a similar procedure. In this manner the entire f(X) function can quickly and accurately be set up.

If the slope of any one segment exceeds 2 volts/volt, it may be preferable to break in two segments at that point rather than one. This gives a maximum slope of 4 volts/volt but reduces the total number of segments available from 9 to 8. The other alternative is to operate with higher gain in the DFG output amplifier. This can be done by putting a coefficient pot between the 1 meg feedback resistor and the amplifier output. The amplifier gain is then increased by a factor equal to the reciprocal of the pot setting.

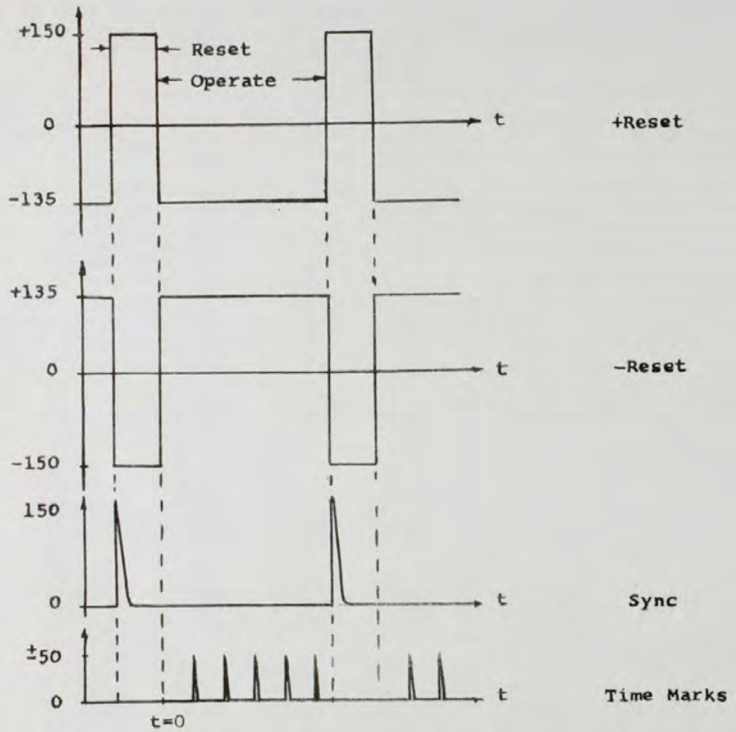


Figure 14-1 :

Time Sequence of Pulses in the Repetitive Control Module

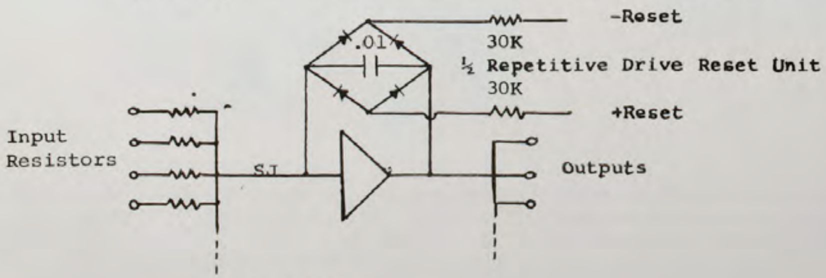


Figure 14-2 :

Operational Amplifier with Repetitive Drive Reset Unit

14. REPETITIVE OPERATION

The repetitive mode in the computer is based on electronic reset of the integrators wherein the capacitors are reduced to 0.01 uF. These are 1% polystyrene units.

To place the pair of integrators in any of the upper areas of the patch panel, or lower areas A2, B2 or C2, in the repetitive mode, throw the corresponding switches near the patchboard frame to the up position. At the same time, the normal integrator capacitor connection to I2 or I3 must be removed, otherwise the 0.01 uF capacitor will merely be placed in parallel with the normal capacitor.

Note also that reset in the repetitive mode is to zero initial conditions, and not to that patched into the IC holes. Special programming may be needed to cover this peculiarity.

Those integrators whose switches are left in the normal, i.e., straight out, position will continue to operate normally whilst the others run under repetitive reset conditions. The Function Switch must be in the OPERATE position for repetitive solution to start.

Figure 1-2 gives detail of the Model 180 Repetitive Control Panel.

Repetitive operate periods are adjustable in steps from 25 milliseconds to 1 second. The integrators are reset to zero in less than 20 milliseconds. Time marks are provided as either positive or negative pulses to modulate the z-axis of the display scope. The maximum positive pulse obtained when the TIME MARK AMPLITUDE control is full counter clockwise; amplitude variation through zero to a maximum negative pulse is obtained by rotating the control in the clockwise direction. This feature enables the operator to use blanking or intensification for time identification on the solution display. Each time mark period is selected by a front panel switch. The periods are 5, 10, 20, 50, and 100 milliseconds. After the start of the solution the first mark is always delayed by one period (see Figure 1).

A positive sync pulse is available to externally trigger the display scope; also the repetitive periods may be triggered with a square wave at the TRIG IN jack. The + and - RESET jacks are provided for viewing the reset pulses on a scope.

The Repetitive Drive Reset Unit includes the .01uf integrating capacitor and diode reset network (see Figure 2). When the reset pulse is applied, the diodes conduct and short the output to the summing junction which is very close to ground potential. In the operate period the diodes are open and the operational amplifier behaves as an integrator with a 0.01uf feedback capacitor.

15. AUXILIARY CONTROLS

The Auxiliary Control Panel (Figure 1-2) controls the special features built into the MUDPAC installation - the thermostatically-controlled oven for the precision computing components, slave operation, overload alarm, and automatic hold on overload.

Working from the top of the panel, these controls are as follows:

A. Oven Controls:

Located at the top of each panel is the oven control switch, indicator light, and fuse. This switch controls the 115v AC to the ovens and works independently of any computer power controls. As such, it is separately fused with a 3 amp fuse (AGC3). The oven light indicates power applied to the oven--not whether the oven is heating or not: i. e., the light will be on regardless of whether the thermostat is on or off.

B. Slaving Control:

Directly below the oven controls on one console only (hereafter referred to as Console #1 or Master Computer) is located a Slave-Independent switch. This controls the slaving operation of the computers when the control interconnect cable is attached to both computers. When this switch is in the independent position, each computer acts independently of the other and no functions are common. For slaving the two computers, put the switch to slave position. This slaves Console #2 to Console #1. In slave operation, Console #1 controls all the functions of Console #2.

C. Overload Alarm:

This control simply activates or deactivates the overload alarm.

D. Auto Hold:

Auto hold, when on, is used in conjunction with the overload alarm. When the computer is in the operate mode, any overload will automatically throw the computer into hold. If the overload condition is corrected, the computer will remain in hold. Several methods of continuing the problem may be used. By remaining in the operate mode and pushing the reset button on this control panel, the computer will automatically continue the problem. This reset refers to resetting the auto-hold circuit only and should not be confused with the reset mode of operation. Another option is to switch the computer mode to reset. This automatically resets the problem, resets the auto-hold, and energizes the pen start feature. Should you want to continue the solution without resetting the computer, yet still get the benefit of delayed start for recorders and pens, switch from operate mode to hold. This will energize the delayed start circuit. Then push the reset button to reset auto-hold. Switching the mode back to operate will then allow the solution to continue with the pen start feature being used.

16. PEN DROP AND MOTOR START

The pen drop and motor start circuit is designed to provide a time delay when switching from RESET to OPERATE or HOLD to OPERATE for the purpose of starting chart drive motors and dropping pens on plotters, etc. A pot is located in the bottom bay of the computer to adjust the time delay between 0 and 4 seconds.

SECTION III - PERIPHERAL EQUIPMENT

1. INPUT EQUIPMENT

No special input equipment is permanently associated with the computer. However, various items may be available when not required in other laboratories. Such items are

Function Generators - square, triangle, sine and pulse, repetitive or triggered.

Random Function Generators.

Enquiries as to their availability should be made from the Technical Officer.

2. OUTPUT EQUIPMENT

The following are permanently assigned to the computer for output display, recording and measurement:

1 Tektronix Model 502 Double-beqm Oscilloscope
1 Offner Model RC 4-channel Pen Recorder with Events Marker
1 PACE Model 1100E 25 cm. x 38 cm. X-Y Plotting Table
1 Digital Measurements DM 2001 Digital Voltmeter

Basic operating instructions for each of these items is set out below. Further information in each case may be found in the relevant Instruction Manual for the particular instrument.

Other input equipment may be available when not required in other laboratories. Such are

Additional Oscilloscopes
Additional Pen Recorders
Counting/Timing Equipment

Enquiries as to availability should be made from the Technical Officer.

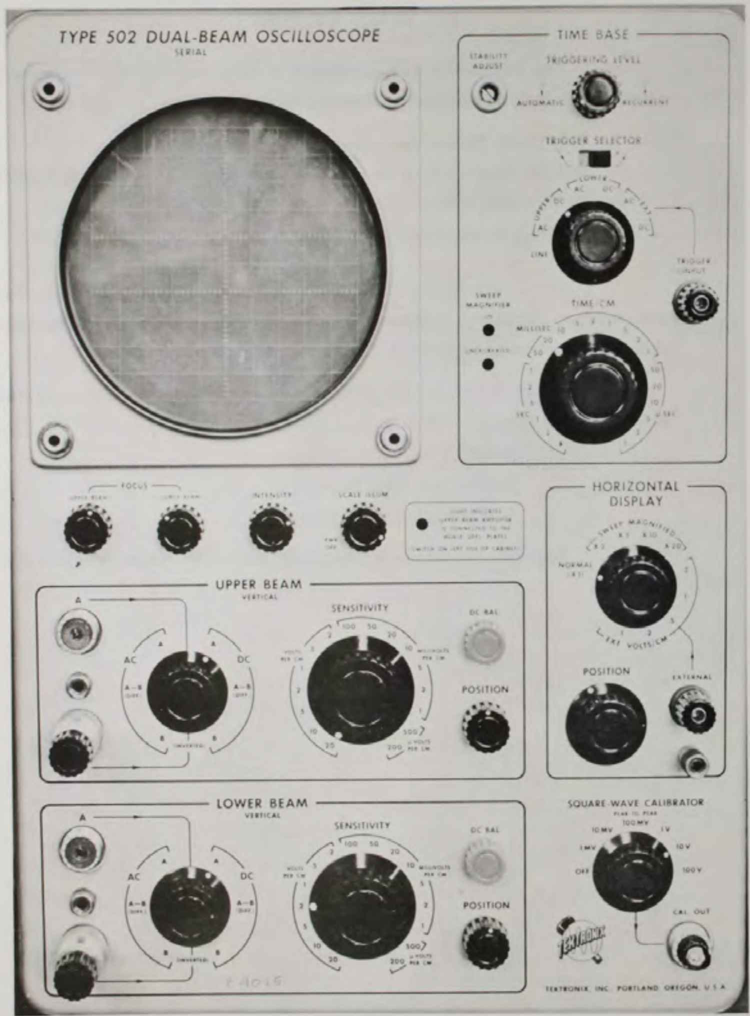


Figure 2A-1, Tektronix Type 502 Dual-beam Oscilloscope

(A1) <u>Tektronix Type 502 Oscilloscope</u>

Figure 2A-1 shows the face of this item.

<u>Input Selection</u>

On the Type 502 Oscilloscope, you can connect single-ended inputs to either the "A" or "B" input connectors of the lower or upper beam amplifiers by rotating the input selector switches to the corresponding positions. The choice of input connections will depend upon the display desired. <u>Waveforms applied to input "B" are displayed in an inverted position on the face of the crt while waveforms applied to input "A" are displayed in the normal upright position.</u> If you are not aware of this difference in the input connectors, it is probable that you will improperly evaluate the results obtained from an input to the "B" connector.

Differential inputs must be connected to both the "A" and "B" input connectors of one amplifier. In the A and B positions of the input selector switch, the corresponding waveforms are displayed on the crt. In the A-B (DIFF) position, the "B" input is algebraically subtracted from the "A" input and the difference is displayed. This feature permits you to eliminate common mode signals, and to observe a waveform which is peculiar to one input.

<u>Input Coupling</u>

Input signals to the vertical amplifiers can be either a.c. or d.c. coupled by placing the input selector switch in the corresponding positions. DC coupling applies both the a.c. and d.c. components of the input signal to the vertical amplifier circuits. This permits you to measure the d.c. voltage level as well as the amplitude of the a.c. component. It is sometimes neither necessary nor desirable to display the d.c. component. In such cases a.c. coupling should be used. With a.c. coupling, a capacitor is placed in series with the input connector to block the d.c. component while at the same time allowing the a.c. component to be displayed.

Input Connections

Here are some precautions you should observe in connecting your oscilloscope to the signal source.

1. Avoid errors in readings due to stray electric or magnetic coupling between circuits, particularly in the leads connected to the input connector. In general, unshielded leads of appreciable length are unsuited for this use. When shielded leads are used, the shields should be grounded to the oscilloscope chassis and to the chassis of the equipment being tested. Coaxial cables are recommended for many purposes. Special care must be taken in the high sensitivity ranges of the oscilloscope due to the low signal level and high amplifier gain.

2. As nearly as possible, simulate actual operating conditions in the equipment being tested. The equipment should have a load on it which is approximately equal to the load encountered in normal operation.

3. Consider the effect of loading upon the signal source due to the input circuit of the oscilloscope. The circuit at the input connectors can be represented by a resistance of 1 megohm shunted by a capacitance of 47 pF. With a few feet of shielded cable, the capacitance may well be 100 pF or more. In many cases, the effects of these resistive and capacitive loads are not negligible.

Triggered Operation

In order to obtain a stable display of some recurrent waveform, it will be necessary for you to trigger the horizontal sweep at the correct instant of time. This will insure that the sweep will start at the same point on the observed waveform for each cycle of operation. The sweep should be triggered either by some waveform bearing a fixed time relationship to the observed waveform or by the observed waveform itself.

Either method will produce the desired stable display. If the waveform which is applied to the upper beam and the waveform which is applied to the lower beam have a definite time relationship to each other it is possible to trigger from either beam and obtain simultaneously a stable display of both waveforms.

The following instructions tell you how to select the proper triggering signal for various applications of your oscilloscope. These instructions also provide information about the advantages and limitations of each triggering mode. You should attempt to become thoroughly familiar with all of the various triggering modes in order that you may obtain maximum use from your instrument. A thorough knowledge of the triggering modes will allow you a greater selection of triggering methods when you are confronted with a definite triggering problem.

How to select the triggering signal source

1. To trigger the sweep from the waveform displayed on the upper beam, set the TRIGGER SELECTOR switch at UPPER AC or UPPER DC.

2. To trigger the sweep from the waveform displayed on the lower beam, set the TRIGGER SELECTOR switch at LOWER AC or LOWER DC.

3. To trigger the sweep at the power line frequency, set the TRIGGER SELECTOR switch at LINE. You would normally use this mode of triggering when you are observing a waveform which bears a fixed time relationship to the power-line frequency.

4. To trigger the sweep from some external waveform bearing a definite time relationship to the observed waveform, connect the external waveform to the TRIGGER INPUT connector and set the TRIGGER SELECTOR switch at EXT AC or EXT DC. External triggering provides definite advantages over other modes of triggering in certain cases. With external triggering, the triggering signal generally remains essentially constant in amplitude and shape. It is thereby possible to observe the shaping and amplification of a signal by each stage of a circuit without resetting the triggering controls for each observation. Also time and phase

relationships between the waveforms at different points in the circuit can be seen. If, for example, the external triggering signal is derived from the waveform at the input to a circuit, the time relationship and phase of the waveforms at each point in the circuit are automatically compared to the input signal by the display presented on the face of the crt.

How to select the triggering mode

Automatic Mode

Automatic triggering is obtained by rotating the TRIGGERING LEVEL control fully counter-clockwise to the AUTOMATIC position. This mode provides a preset triggering level which is set to allow triggering at the average voltage point of the applied waveform. The sweep runs at approximately a 50 cycle rate when no triggering signals are applied. Automatic triggering can be used with triggering signals obtained from the LINE, UPPER, LOWER, or EXT. positions of the TRIGGER SELECTOR switch, but for most waveforms, it is useful only for triggering at frequencies above approximately 50 cycles. Automatic triggering saves considerable time in observing a series of waveforms since it is not necessary to reset the triggering level for each observation. Other modes are normally used only for special applications or where stable triggering is not attainable in the automatic mode.

DC Mode

The d.c. mode is selected in the UPPER DC, LOWER DC and EXT DC positions of the TRIGGER SELECTOR switch. This mode of triggering is particularly useful in triggering from waveforms which are not adaptable to the a.c. mode, such as random pulse trains or very low frequency waveforms. Random pulse trains pose a special problem in the a.c. mode since the random occurrence of the input waveforms causes the average voltage level to shift. This in turn may cause the triggering level to shift to an unstable point. This problem is not encountered in the d.c. mode since the triggering point is determined only by instantaneous voltages.

In the d.c. mode, when the triggering signal is obtained from either the lower or the upper beam amplifiers, varying the respective vertical position controls will change the triggering point. For this reason, you may find it necessary to readjust the TRIGGERING LEVEL control when you change the vertical position of the trace. If you desire to eliminate this effect, you can use the a.c. mode providing the triggering signal is otherwise suitable for this mode of operation. In the d.c. mode, the d.c. level of external triggering signals will also effect the triggering point. Generally, when the triggering signal is small compared to its d.c. level, the a.c. mode should be used.

AC Mode

The a.c. mode is selected in the LINE, LOWER AC, UPPER AC, and EXT AC positions of the TRIGGER SELECTOR switch. This mode provides stable triggering on virtually all types of waveforms. As a general rule, however, the a.c. mode is unsatisfactory for triggering with low amplitude waveforms at frequencies below approximately 15 cycles. This figure will vary depending upon the amplitude and shape of the triggering waveform and should not therefore be set as an absolute standard. Triggering at frequencies below 15 cycles can be accomplished when higher amplitude triggering signals are used.

In the a.c. mode, the triggering point depends on the average voltage level of the triggering signals. If the triggering signals occur at random, the average voltage level will vary, causing the triggering point to also vary. This shift of the triggering point may be enough so that it is impossible to maintain a stable display. In such cases you should use the d.c. mode.

How to select Triggering Slope

If you wish to trigger the sweep on the rising (positive slope) portion of the triggering waveform, place the TRIGGER SELECTOR switch at +. If you wish to trigger on the falling (negative slope) portion of the triggering waveform, place the TRIGGERING SELECTOR switch at -.

How to set the Triggering Level

In the a.c. and d.c. triggering modes, the TRIGGERING LEVEL control determines at which point on the triggering signal the sweep is triggered. Using this control, the sweep can be continuously triggered at any point on the waveform so long as the slope of the waveform is great enough to provide stable triggering. In the DC mode, the sweep cannot be triggered with any degree of stability at the top of a square wave, for example, because the time that the voltage remains constant is comparatively long. As a result, the sweep triggers at random points along the top of the square wave producing considerable trace jitter.

You can use the same method to set the TRIGGERING LEVEL control for either the a.c. or d.c. mode. After selecting the triggering slope, rotate the TRIGGERING LEVEL control fully counterclockwise to the AUTOMATIC position. Then rotate the TRIGGERING LEVEL control clockwise until the sweep no longer triggers. Continue to rotate the control in the clockwise direction until the sweep again triggers and a stable display is obtained. Further rotation of the control in the clockwise direction causes the sweep to trigger at more positive points on the triggering waveform.

Free-Running Operation

With the Type 502, you can get a periodic free-running sweep, independent of any external triggering or synchronizing signal by rotating the TRIGGERING LEVEL control fully clockwise to the RECURRENT position. This permits you to observe the upper- and lower-beam traces without an input signal.

Magnifier

To expand a particular part of the display horizontally, first use the Horizontal POSITION control to position that part of the display so that it falls at the center of the graticule. Then turn the HORIZONTAL DISPLAY switch to the magnification desired. The portion of the display at the center of the graticule will then be expanded 2, 5, 10, or 20 times depending on the setting of the HORIZONTAL DISPLAY switch. At the same time, the SWEEP MAGNIFIER ON indicator lamp will light, indicating that the display has been expanded. Any portion of the original unmagnified display can then be shown by rotating the Horizontal POSITION control.

In magnified sweep operation, the sweep rate is multiplied by the magnification. This means that the time per centimeter indicated by the TIME/CM switch must actually be divided by the magnification to obtain the correct time required for the sweep to move one centimeter. For example, if the TIME/CM switch is set at 5 MILLISEC, and the magnifier is set at 5X, the true time per centimeter is 5 milliseconds divided by 5, or 1 millisecond per centimeter.

Magnifier sweep rates are all calibrated within 3% accuracy so long as their true time per centimeter is 1 microsecond or more. Sweep rates faster than this are uncalibrated and may be nonlinear. The SWEEP MAGNIFIER UNCALIBRATED indicator lamp lights whenever the maximum calibrated sweep rate is exceeded, to indicate that the sweep is uncalibrated.

EXTERNAL Horizontal Input

On the Type 502, it is possible to horizontally deflect one or both of the spots across the screen by means of some externally derived waveform, rather than by means of the internal sweep circuits. This permits the oscilloscope to be used for either single or dual-beam X-Y curve tracing.

For single-beam applications where equal horizontal and vertical-deflection factors are desirable, the upper-beam amplifier can be switched to the crt horizontal-deflection plates by placing the HORIZ.DEF. PLATE SELECTOR switch at the UPPER BEAM AMP. position. This type of operation provides 200 μv/cm to 20 v/cm sensitivity and differential input for both horizontal and vertical deflection. The lower beam is used for this function while the upper beam is automatically positioned off the screen.

A panel light indicates when the upper-beam amplifier is connected to the horizontal-deflection plates.

For dual-beam applications, an external waveform can be applied to the horizontal amplifier by connecting the waveform to the EXTERNAL connector. The horizontal deflection sensitivity is controlled by the setting of the HORIZONTAL DISPLAY switch. The HORIZ. DEF. PLATE SELECTOR switch must be in TIME BASE AMP position for dual-beam applications.

Voltage Measurements

Accurate voltage measurements of inputs to the vertical amplifiers can be made using the calibrated deflection factor feature of the Type 502. The following instructions tell you how to use the oscilloscope for this purpose and how to obtain the greatest possible accuracy in your measurements. It is important that proper techniques be used in order that errors are not introduced in the results.

During voltage measurements, you should always display the waveform across as much of the crt face as is possible since, as a general rule, the accuracy of your measurements will increase as the vertical size of the displayed waveform is increased. In measuring voltages, it is important to remember that the width of the trace may be an appreciable part of the overall measurement and care should be used that the trace width is not included in the vertical deflection readings you obtain. You should consistently make all your readings from one side of the trace. If the bottom side of the trace is used for one reading, it should be used for all succeeding readings.

How to measure the a.c. component of a waveform

For measuring the a.c. component of a waveform, a.c. coupling is normally used since it is usually not advantageous to display the d.c. component of the waveform being measured. AC component voltage measurements can usually be made with d.c. coupling also, but there is normally no particular advantage in doing so. To obtain peak-to-peak voltage measurement, perform the following steps:

1. Through the use of graticule, measure the vertical distance in centimeters from the level of the positive peak to the level of the negative peak.

2. Multiply the setting of the SENSITIVITY control by the distance measured to obtain the indicated voltage.

<u>How to measure instantaneous voltages</u>

The method used to measure instantaneous voltages is very similar to the method described previously for a.c. component voltage measurements. A reference line must be established on the crt screen. The actual voltage measurement is taken with respect to this reference line. If, for example, the voltage measurement is to be made with respect to +100 volts, the reference line would correspond to +100 volts. In the following procedure the method is given for establishing this reference line as ground since measurements with respect to ground are by far the most common type made. The same general method may be used to measure voltage with respect to any other potential, so long as that potential is used to establish the reference line.

<u>CAUTION</u>

To prevent saturation of the vertical amplifiers, the peak voltage to ground at any amplifier input connector must not exceed 200 volts on 5, 10, and 20 VOLTS PER CM ranges; 20 volts on the .5, 1, and 2 VOLTS PER CM ranges; and 2 volts on all other ranges.

To obtain a voltage measurement with respect to ground, perform the following steps:

1. To establish the reference line, touch the input line to the oscilloscope ground terminal, and rotate the TRIGGERING LEVEL control fully clockwise to the RECURRENT position.

2. Vertically position the trace to a convenient point on the face of the crt. This point will depend upon the polarity and amplitude of the input signal, but it should always be chosen so that the trace lies along one of the major divisions of the graticule. The graticule division corresponding to the position of the sweep is known as the ground reference line. (Do not adjust the vertical positioning control after this reference point has been established).

3. Remove the input line from ground and connect the probe to the signal source. Adjust the TRIGGERING LEVEL control for a stable display.

4. Measure the vertical distance in centimeters from the point to be measured to the ground reference line by use of the graticule.

5. Multiply the setting of the SENSITIVITY control by the distance measured to obtain the indicated voltage.

You should remember in determining the polarity of voltages measured in this fashion that inputs applied to the "B" input connectors are inverted on the face of the crt. Consequently, the apparent polarity of these inputs is opposite the true polarity. To prevent possible confusion as to polarity it is usually best to use the "A" input connectors for voltage measurements with respect to ground.

<u>Time Measurement</u>

Accurate elapsed time or time interval measurements can be made by utilizing the calibrated timebase feature of the Type 502 Oscilloscope. The sweeps are calibrated so that the beams are deflected across the screen at known rates. Since the beam travels completely across the screen in a known period of time, the time required for the beam to travel any portion of the distance can be determined. By measuring the horizontal distance between points on the displayed waveform, and by knowing the sweep rate, you can determine the time interval between the two points. For accurate measurements be sure the same reference point is used on both pulses. The method for measuring a time interval is as follows:

1. Using the graticule, measure the horizontal distance in centimeters between the points whose time interval you wish to find.

2. Multiply the distance measured by the setting of the TIME/CM control to obtain the apparent time interval.

3. Divide the apparent time interval by the magnification indicated by the setting of the HORIZONTAL DISPLAY switch to obtain the correct time interval.

Frequency Measurement

The frequency of a periodically recurrent waveform can be determined if the time interval (period) of one complete cycle of the waveform is known. This time interval can be measured by means of the procedure described in the preceding paragraph. The frequency of a waveform is the reciprocal of its time interval.

DC Balance Adjustment

If the trace moves vertically as the SENSITIVITY control is rotated, this indicates a need to readjust the DC BAL control. This control is used to compensate for any d.c. unbalance in the vertical amplifier. This unbalance will be particularly noticeable on the high sensitivity ranges of the SENSITIVITY control. To adjust the DC BAL control, ground the oscilloscope input, place the SENSITIVITY control at 20 VOLTS PER CM, and rotate the TRIGGERING LEVEL control to the RECURRENT POSITION. Set the DC BAL control at mid range and position the sweep so that it lies under the proper base line. Rotate the SENSITIVITY control to the 200 VOLTS PER CM position, pausing at each range to adjust the DC BAL control so that the trace remains on the base line. (If the DC BAL control does not have sufficient range, it will be necessary to readjust the appropriate COARSE DC BAL control located inside the instrument.)
The trace should now remain stationary as the SENSITIVITY control is turned through its entire range of positions.

AUXILIARY FUNCTIONS

Calibrator

The calibrator is a source of accurately calibrated square waves at a frequency of approximately 1 kilocycle (+ or - 30%). The output amplitude is accurate within 3% of the SQUARE-WAVE CALIBRATOR switch settings for no load conditions. The primary function of the calibrator is to provide a convenient method for checking the calibration of the vertical-deflection system. It can be used for other purposes, however, if certain limitations are kept in mind.

The output impedance of the calibrator various with the output-voltage setting. It is as low as 10 ohms in the 1 MV position of the SQUARE-WAVE CALIBRATOR switch and as high as 1.8 kilohms in the 10 V position. In the 100 V position, the output impedance is approximately 170 ohms when the circuit is loaded by a resistance of not less than four kilohms. When the switch is at any position other than 100 V, the output may be loaded with any impedance without damaging the components. See Table 1 for the approximate output impedance for each position of the SQUARE-WAVE CALIBRATOR switch.

Table 1

Approximate Output Impedance of Calibrator

Output Impedance	SQUARE-WAVE CALIBRATOR switch setting
*170 ohms	100 V
1.8 kilohms	10 V
200 ohms	1 V
900 ohms	100 MV
100 ohms	10 MV
10 ohms	1 MV

*Do not load with less than 4 kilohms.

Note

All output impedance figures given for the calibrator are made with the assumption that the output cathode follower is conducting.

Trace-brightness (intensity) modulation

To couple markers or other signals into the crt cathodes for trace-brightness modulation, disconnect the ground strap at the rear of the instrument and apply the signal between the CRT CATHODE binding post and GND. This will simultaneously apply the signals to the upper and lower beam cathodes. At normal brightness, positive signals of about 25 volts will cut the beams off. Always replace the ground strap when you are not intensity modulating the beams.

Graticule illumination

The graticule lighting control, labeled SCALE ILLUM, can be adjusted to suit the lighting conditions of the room. A green filter is supplied with the instrument which can be used for increased contrast. This filter should be mounted next to the crt face so it does not block the light from the graticule lines.

The graticule of the Type 502 Oscilloscope can be illuminated so that it appears to have either red or white graticule markings. The markings can be quickly changed from white to red or from red to white by removing the graticule cover and inverting the graticule. As a general rule, white graticule lines are superior to red for photographic purposes.

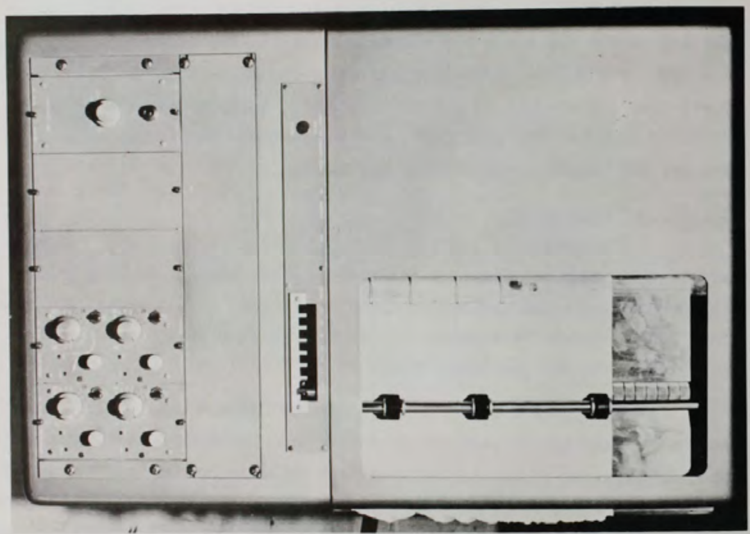


Figure 2B-1, Offner Type RC Multichannel Pen Recorder

(B1) Offner Type RC Multichannel Pen Recorder

This recorder is currently fitted with 4 recording pins and an event marker pen. A top view of the instrument is shown in Figure 2B-1.

(a) Preliminary Checks

(i) Remaining Recording Paper

Checking the remaining recording paper.

(ii) Recording System

Turn the Function switch to the MOTOR position, select a paper speed of 5 mm/sec. If required, align all pens or styli to their respective zero reference lines on the recording paper.

(iii) Ink Pens

Check the ink level in each of the inkwells. Should the ink level be low, refill the inkwells according to instructions given in the section on the paper drive assembly.

Prime each non-writing pen by raising the inkwell cap approximately 1/4 inch, block the vent hole of the cap with the finger, and press down on the cap. This produces enough pressure to force ink through the inkfeed system. Repeat if necessary.

The inkwells are placed in their fully depressed positions, providing a capillary ink-feed, when recording d-c of slowly varying signal information. The inkwells are elevated to provide a gravity ink-feed for high frequency recordings.

After priming all non-writing pens, push the paper drive assembly back into the enclosure and replace the retaining screws.

(iv) Calibration

(a) Set all selector switches to the OFF Position.

(b) Turn Function switch to the OPERATE position.

(c) Select a paper speed of 1 to 5 mm/sec, as desired.

(d) Adjust the Zero Setting control of each amplifier so the pen or stylus aligns with the zero reference line on the recording paper.

(e) Set the sensitivity selector switch of one of the amplifiers to the 2 CM position.

(f) In the event that a 2 cm stylus deflection is not obtained, adjust the Gain control setting on the front panel of the respective channel.

(g) Repeat this procedure for all amplifiers to calibrate the complete assembly.

(b) <u>Paper Drive</u>

(i) <u>Motivate Paper Drive</u>

Start paper drive by turning the Function switch to the MOTOR position.

(ii) <u>Select Paper Speed</u>

Slide the speed selector shift lever to the desired speed, release lever and allow to engage unassisted. <u>Do not force lever into the engaged position</u>.

(iii) <u>Loading Recording Paper</u>

Attention must be paid to the types of cores employed in recording paper rolls. Type B cores ($\frac{3}{4}$" I.D.) are employed for curvilinear recording papers.

1. Pull the hinged support arm from the paper roll supporting shaft.

2. Remove the roll retaining knob by revolving it in a counter-clockwise direction.

3. Remove the old paper roll core.

4. Check the new paper roll for even winding to assure minimal paper weave in operation, particularly with long length rolls. The surface formed by the edge of the roll, on the inner end of the installed paper, must be flush with the keyed end of the core. When the paper is unevenly wound or when the core is not flush with the end of the roll, place the inner end of the roll on a flat surface and tamp the opposite end with the hand until corrected.

5. Insert the new roll of paper with the notched end of the core engaging with the key on the inner disc.

6. Replace the retaining knob and tighten it against the core.

7. Return the hinged support arm to the shaft assembly. This arm should snap into place when the pin spanning the center hole of the paper tension knob is aligned with the slot in the end of the support shaft.

8. Release the pressure roller from the drive roller.

9. Feed the recording paper under the styli and then between the drive roller and pressure rollers.

10. Reset the pressure roller to clamp the recording paper to the drive roller.

11. Start paper drive, using medium paper speed and allow paper to align in paper drive assembly.

(c) Amplifiers

(i) Panel Controls

The first-section amplifier controls are located on the upper part of the front panel and the second-section amplifier controls are located on the lower part of the panel.

On the sensitivity control, note that a 2CM position is provided adjacent to the OFF position. This position is used for calibration of each channel. Note the preamplifier positions marked X .02, X .1, and X1. These positions are used when preamplifiers are installed, which is not the case in this particular recorder.

(ii) Operating Controls

The operating controls found on the front panel of the amplifier are the sensitivity selector switch, the zero setting control and the high frequency switch.

(iii) Sensitivity Selector Switch

The function of the sensitivity selector switch is three-fold. First, it permits the selection of the desired gain for recording. Sensitivities ranging from 10 millivolts per centimeter to 50 volts per centimeter are available. Second, it permits the calibration of the system.

(iv) Zero Setting Control

When using the amplifier, zero setting is obtained by applying the setting signal to the feed-back circuit of the amplifier. The amount of zero suppression so available is limited primarily by the signal handling capacity of the input stage, and is approximately ± 20 times full scale deflection.

The standard zero setting potentiometer has a taper with low slope in the central portion. This is provided to permit zero setting to be more readily accomplished with less critical adjustment, when using the preamplifier at high sensitivity. With such use, normally only the central portion of the potentiometer will be employed.

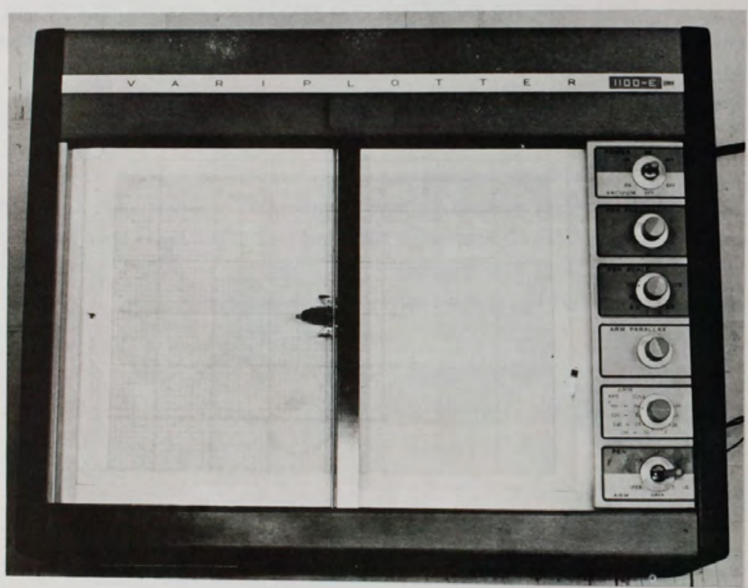


Figure 2C-1, PACE 1100E Variplotter (X-Y Plotting Table)

(C1) PACE 1100E Variplotter (X-Y Plotting Table)

This is a device whereby two variables may be plotted against each other, or one variable against time, on an area 25 cm x 38 cm. The speed is rather slow compared with a pen recorder, but it is a very commonly used output device when the computer time scale is set sufficiently slow.

It may also be used with a curve follower attachment to generate empirical or arbitrary functions.

Figure 2C-1 shows a view of the instrument.

(i) Variplotter Controls

In order to properly operate the VARIPLOTTER the operator should thoroughly understand the function of each of the VARIPLOTTER controls described in the following paragraphs. Before attempting to operate the VARIPLOTTER allow at least 15 minutes warm-up time. This warm-up period permits stabilization of the various plotter circuits.

a Control Panel

Control	Function
POWER-VACUUM	Controls the application of primary power to the VARIPLOTTER. In the OFF-OFF position power is removed from all circuits and a friction brake is applied to the arm drive system. In the ON-OFF position power is applied to all circuits except the vacuum pump motor, the servo motor control windings and the chopper solenoid. The friction brake is also released from the arm drive system. (Even though the power cable is not plugged into a primary power source the friction brake is released when the switch is placed in the ON-OFF position.) In the ON-ON position power is applied to all circuits including the vacuum-pump motor.

PEN PARALLAX	Controls the null position of the pen with a zero input. This control is used to determine the Y position of the plot zero point (on-board 0,0).
PEN SCALE	Determines the deflection sensitivity of the pen servo circuit. This control is used to set the size of the plot in the Y direction for the input data.
ARM PARALLAX	Controls the position of the arm on the plotting surface with a zero input. This control is used to determine the X position of the plot zero point (on-board 0,0).
ARM SCALE	Determines the deflection sensitivity of the arm servo circuit. This control is used to set the size of the plot in the X direction for the input data.
PEN-ARM	Controls the operation of the pen and arm. In the UP-STAND position the pen raises from the plotting surface and moves to the center of its travel. The arm moves to the extreme right of the plotting surface. The pen and arm do not respond to input data signals. In the UP-OPER position the pen and arm respond to input signals, but, the pen is maintained in the raised position. In the DOWN-OPER position the pen and arm respond to input signals and the pen may be dropped to the plotting surface. The actual dropping of the pen is also dependent on the PEN LIFT switch. (See the following sub-paragraph b).

b Data Input Panel Controls

Control	Function
PEN LIFT	Permits control of the pen position (up or down) from a local or remote source. In the LOCAL position the pen is controlled by the PEN-ARM switch on the control panel. In the REMOTE position the pen may be controlled by an external switch (used in conjunction with the PEN-ARM switch) connected between J11-7 and 26 (DATA CONNECTOR).

PEN CALIBRATE — Adjusts the reference potential applied to the pen mandrel. The adjustments are used to calibrate the accuracy of the pen deflection in reference to the input signals. R19 serves as the coarse adjustment and R21 as the fine adjustment R21 is accessible at the data input panel.

ARM CALIBRATE — These adjustments perform the same function as R19 and R21, except for the arm mandrel. R22 is the fine adjustment and is accessible at the data input panel.

(ii) Paper Installation

The standard graph paper (EAI 955.009) supplied with the plotter is translucent, thus facilitating the alignment of the cross-hatch lines of the paper with the machined vacuum grooves of the plotting surface.

Plain paper may be squared on the plotting surface either by eye (comparing the vacuum grooves with the edges of the paper) or by drawing pencil lines parallel with the paper edges and aligning these lines with the vacuum grooves.

Opaque paper may be squared by comparing the graph lines (or the edge of plain paper) with the arm back edge.

(iii) Parallax Control Adjustment

The PEN and ARM PARALLAX controls are used to set the location of the 0,0 point for the data to be plotted. The desired location of the 0,0 point is dependent on the parameters of the data and/or the desired size of the finished plot. To adjust for proper parallax, proceed as follows:

a. Prepare the plotter for normal operation and install a sheet of plotting paper.

b. Place the PEN-ARM switch in the UP-OPER position. This permits moving the pen and arm across the plotting surface without marking the surface with an ink line.

c. Insert a signal of X = 0 and Y = 0 to the pen and arm servo inputs.

Note

If possible the X = 0 and Y = 0 signals should be obtained from the plotting data source. This eliminates the possibility of error due to the source 0-0 voltage being slightly above or below the VARIPLOTTER chassis ground.

d. Adjust the PEN and ARM PARALLAX controls so that the pen-point rests exactly over the desired 0,0 point. (Depressing the pen slightly with a finger tip will permit a more exacting setting of the pen-point).

e. Momentarily place the PEN-ARM switch in the DOWN-OPER position to record the 0,0 point. (If it is not desired to plot this point in ink, carefully record the position with a pencil dot).

(iv) Scale Control Adjustment

The VARIPLOTTER is available with either stepped or continuously variable PEN and ARM SCALE controls. The adjustment of these controls determines the size of the data plot.

a. Stepped Scale Control Adjustment

Set the PEN and ARM SCALE controls to the settings that will give maximum deflection of the pen and arm for the maximum input data magnitude without deflecting the pen or arm out of the desired plotting area.

b. Continuously Variable Scale Control Adjustment

The continuously variable PEN and ARM SCALE FACTOR adjustment permits the expansion of a data-plot to the maximum possible size on the plotting surface. The procedure for adjusting these controls is outlined in the following steps:

(1) Set the variable potentiometers of both the PEN SCALE and ARM SCALE to a minimum setting (fully counter-clockwise).

(2) Set the stepped PEN and ARM SCALE switches to the maximum setting that will retain the maximum-magnitude X and Y co-ordinates of the plot within the limits of the plotting area.

(3) Apply d.c. voltages to the VARIPLOTTER pen and arm servo inputs equal in sign and magnitude to the maximum X and Y co-ordinates of the data to be plotted.

(4) Adjust the variable potentiometers for maximum deflection of the pen and arm from the 0,0 point.

(v) Pen and Arm Calibrate Adjustments

The PEN and ARM CALIBRATE control screwdriver-adjustments located on the data input panel are the fine adjustments, R21 and R22 respectively. These controls are used to calibrate the SCALE control settings with respect to the input-signal reference level. In most cases it will be found that the range of adjustment afforded by these controls is sufficient; however, if a greater range is required R19 and R21 can be used. The PEN and ARM CALIBRATE control adjustments should be checked at least daily, and more frequently if the input-source reference voltage tends to vary. The PEN and ARM CALIBRATE settings should also be checked in changing signal sources, if the sources have different reference voltage supplies.

The VARIPLOTTER generally is more accurate in deflection distance-per-volt than the graph paper cross-hatch line spacing. Therefore if it is desired to plot a curve using the graph-paper lines as reference it is necessary to calibrate the pen and arm using the cross-hatch lines as a guide.

Note

Paper has a tendency to stretch or shrink depending on atmospheric conditions; for maximum accuracy the PEN and ARM CALIBRATE settings may be checked for each sheet of paper.

The following is a procedure for setting the CALIBRATE controls:

a. Using the PEN and ARM PARALLAX controls, set the X-Y 0,0 point in the lower left-hand corner of the plotting surface. This point should be accurately recorded; if it is undesirable to plot this point with the plotter pen, use a pair of crossed lines as reference, or in the case of plain paper carefully and accurately record the point in pencil.

b. Set the PEN and ARM SCALE controls to the 5 volts per cm. position (0.05 volt per cm. scale if high sensitivity networks are used). If the VARIPLOTTER has a continuously variable SCALE FACTOR set these potentiometers fully clockwise.

c. Using the input data source equipment, apply a +100 volt signal (1 volt for high sensitivity) to the servo arm input.

d. Place an accurate scale on the plotting surface and set the ARM CALIBRATE control for exactly 20 cm. of deflection of the arm along the X axis from the X = 0 point (use the pen point as reference).

Note

If it is desired to have the plot correspond to the lines of the cross-hatch paper, use the cross-hatch lines as reference for this adjustment. Because the plotter operates with greater accuracy and in closer tolerance than most cross-hatched paper is printed, it may be necessary to touch-up the CALIBRATE control to minimize the error between arm deflection and the graph paper line spacing if the graph lines are to be used as reference.

e. Repeat steps c and d for adjustment of the PEN CALIBRATE control.

Figure 2D-1, Digital Voltmeter DM2001

(D1) **Digital Voltmeter DM2001**

This instrument gives conveniently a direct digital presentation of a DC voltage. It may also be used with differential input up to 50 volts with respect to ground.

Figure 2D-1 shows the front face of the instrument.

Specification

Voltage Input Ranges	(1) ± .15995V (2) ± 1.5995V (3) ± 15.995V (4) ± 159.95V (5) ± 1599.5V (6) ± Externally selected, i.e., elastic scale.
Accuracy	± .05% reading or 5 least significant digits, whichever is greater (final number reads 0 or 5 only)
Input Impedance	Ranges 1, 2 and 6, 2000 MΩ All other ranges, 10 MΩ ± 0.1%
Total Conversion Time	20 msec.
Polarity Indication	Automatic by red/black colour background.
Decimal Point Indication	Automatic with range switching (no decimal point on Range 6).
Range Switching	Manual or by external selection.
Interference Rejection	(a) Switched low-pass filter, .02 sec. or .1 sec. (b) Dead zone control variable between 5 and 50 digits. (c) Resolution variable: 5, 10 or 20 digits.

Signal Sampling Modes	(a) Pushbutton (b) Internal trigger (50 per second) (c) External trigger (up to a maximum of 50 per second) (d) Automatic (conversion initiated by changing input) (e) Maximum reading (conversion initiated by changing input) (f) Minimum reading (conversion initiated by changing input).
Display	In-line illuminated numerals
Signal Level	External trigger +9 V, rise time $< 2\ \mu s$, duration > 1 ms.

(i) <u>Normal Use</u>

Set the controls as follows:

(1) Set the RANGE switch to the lowest range which includes the voltage to be read. The voltage will then be indicated to the maximum number of significant figures.

(2) Set the RESOLUTION switch to 5. This setting provides maximum accuracy of reading.

(3) Set the MODE switch to AUTO. The reading follows changes in signal which exceed the dead zone set by the TRIP potentiometer.

(4) Set the TRIP potentiometer to 5. This reduces the dead zone to minimum so that the indicated reading cannot differ from the signal voltage by more than 5 in the last figure.

(5) Set the FILTER CR switch to .02. The rate of response is then as fast as the observer can follow, whilst high rejection of 50 c/s ripple and useful attenuation of higher frequencies and noise are obtained.

(ii) <u>Hum and Noise</u>

The presence of hum or noise on the input signal may cause the instrument to trip continuously. If this occurs, useful readings may be obtained in one of the following ways:

(1) Set FILTER CR switch to .1. This increases the attenuation of higher frequencies and noise but introduces a delay so that the time response of the instrument is degraded.

(2) If it is inadmissible to slow the response, set the FILTER CR switch back to .02 and slowly increase the setting of the TRIP potentiometer until steady readings are obtained. This increases the dead zone so that smaller fluctuations of input signal are ignored. The reading obtained will be the mean of the limits between which the signal is fluctuating.

The TRIP potentiometer does not affect the accuracy of the reading but determines when a new reading shall be taken. When a new reading is taken, it will be that nearest to the input. Subsequent changes may occur within the dead zone and a check on this can be made by operating the manual push button to initiate a fresh reading.

It may be necessary to increase the attenuation of ripple and noise as well as increasing the dead zone in order to obtain useful readings. If this is so, set the FILTER CR switch to .1 and then slowly increase the setting of the TRIP potentiometer from 5 until steady readings are obtained. The dead zone should not be made larger than is necessary to obtain stable operation. The reading will then be mid-way between the limits of the input voltage, since (input + trip setting) and (input - trip setting) are both just outside the varying input. This condition is particularly useful where the input carrier very low frequency beats, e.g., 1 c/s, where the mean will be read with virtually no loss of accuracy.

MUDPAC Manual

(iii) Maximum Reading

If it is required to record the most positive excursion of a changing signal over a period of time, set the MODE switch to MAX. The instrument then follows only positive changes in signal voltage. For example, if a signal has varied between -2 V and +3 V, the final reading of the instrument will be +3 V. If the signal has varied between -8 V and -4 V, the final reading wil be -4 V. In this mode the dead zone is again determined by the setting of the TRIP potentiometer. A fresh sequence is initiated by depressing the push button.

(iv) Minimum Reading

If it is required to record the most negative excursion of a changing signal over a period of time, set the MODE switch to MIN. The operation is similar to that in the MAX mode except that only negative changes in signal voltage are followed. Thus in the previous example, readings of -2 V or -8 V, respectively, would be recorded.

(v) One Shot Readings

Single shot readings are obtained by setting the MODE switch to MAN and initiating a reading either by depressing the manual pushbutton or by injecting a +9 V step at SK2/A9. In this mode, it is essential to set the FILTER CR switch to 0 or, otherwise, to take several readings to confirm that the filter circuits have charged to a steady value. No matter in what mode the instrument is operating, depressing the pushbutton or injecting an external trip signal will initiate a fresh reading.

(vi) Unrelated Signals

When measuring unrelated signals as, for example, in systems applications, always set the FILTER CR switch to 0.

(vii) Reducing Resolution

In some applications, usually in systems work, it is convenient to round off the readings to four significant figures, i.e., to a scale of 1599. This cannot be done by ignoring the fifth figure since 10000 indicates an input between 9997.5 and 10002.5. On a scale of 1599, 1000 should be indicated for an input between 999.5 and 1000.5. The RESOLUTION switch provides this facility, making the necessary adjustments to the circuitry and the display. Thus, when set to 10, the reading is to a scale of 1599 and the fifth indicator remains at 0. When set to 20, the instrument reads even numbers only on a scale up to 1598, the odd numerals in the fourth, and the 5 in the fifth, figure being suppressed.

(viii) Continuous Readings

To obtain continuous readings, independent of whether the input signal varies, set the MODE switch to CONT. Readings are repeated at a repetition frequency of 50 c/s. If the reading flickers between two possible readings, the conversion process may be arrested by depressing the manual pushbutton. The continuous mode should be used only for steady input signals. If the signal is varying, better results are obtained by operating in the AUTO mode.

(ix) External Trip using Contact Closure

By connecting a 1 MΩ resistor between pins A9 and A11, a trip pulse will be generated by closure of contact between pin A9 (External trip) and pin C12 (Common rail).

(x) Floating Input

The D.M. 2001 is not a differential input instrument, but may be operated under floating input conditions provided certain precautions are strictly observed. The input connections and cable coding are as follows:

Cable Code	Internal Connections	External Connections	
		Floating Input	Normal Input
WHITE	Signal input	Signal, high potential	Signal
BLACK	Common rail	Signal, low potential	Signal earth-
GREEN	Instrument chassis and mains earth	External earth	Black & green leads connected together.

The instrument is normally supplied with the black and green input leads connected together. These leads must be separated for floating input operation. If the instrument is used frequently with floating input, it is convenient to connect a crocodile clip to the green lead.

CAUTION:

On no account should the voltage between common rail and chassis, i.e., between the signal low potential and earth, exceed 50 V peak, otherwise serious damage to the instrument may result.

When used with a floating input, the green lead must be connected to an external earth and the impedance between signal low potential and earth must be low, otherwise errors in reading will occur.

3. SPECIAL ANCILLARY EQUIPMENT

There is no special ancillary equipment presently available for use with MUDPAC.

4. POWER SUPPLIES

The following power supplies are available in the Analogue Computation Laboratory.

<u>Alternating Current</u>

240 V	50 c/s	single phase,	several outlets at 2 KW
400 V	50 c/s	three phase,	27 KW (35 MW)

<u>Direct Current</u>

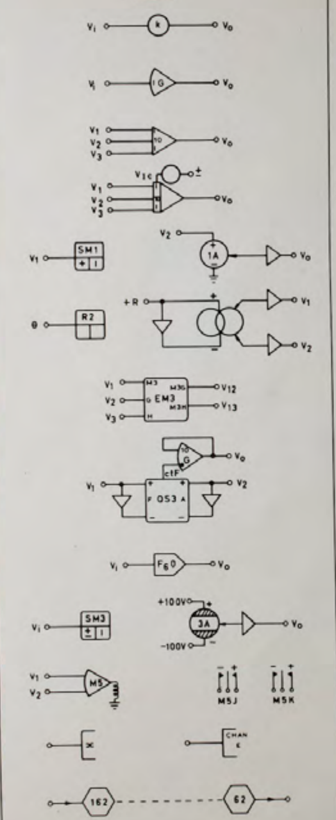
0-40-120-180-240 V @ 5A from batteries
0-4-8-12-16-20 @ 5A from batteries
220 V @ 35A from generator
0-110-220 V @ 25A from balancer set.

<u>Miscellaneous</u>

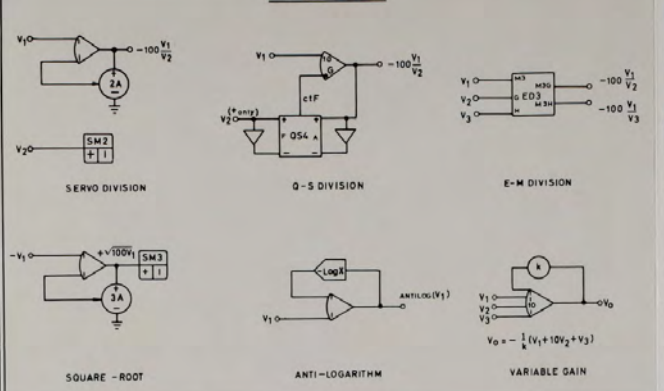
Other alternating current supplies at different voltages and frequencies, and regulated direct current may be available from equipment not required in other laboratories. Enquiries should be made from the Technical Officer.

NOMENCLATURE	FUNCTION
POTENTIOMETER	$V_o = kV_i$
HIGH GAIN AMPLIFIER	$V_o = -GV_i$
SUMMING AMPLIFIER	$V_o = -(V_1 + 10V_2 + V_3)$
INTEGRATOR	$V_o = -V_{ic} - \int_0^t (V_1 + 10V_2 + V_3)\,dt$
SERVO MULTIPLIER	$V_o = -\frac{V_1 V_2}{100}$
SERVO RESOLVER	$V_1 = -R\sin\theta$, $V_2 = -R\cos\theta$
ELECTRONIC MULTIPLIER	$V_{12} = -\frac{V_1 V_2}{100}$, $V_{13} = -\frac{V_1 V_3}{100}$
QUARTER SQUARE MULTIPLIER	$V_o = -\frac{V_1 V_2}{100}$
DIODE FUNCTION GENERATOR	$V_o = f(V_i)$
SERVO FUNCTION GENERATOR	$V_o = f(V_i)$
RELAY COMPARATOR	+ CONTACT WHEN $(V_1 + V_2) > 0$; – CONTACT WHEN $(V_1 + V_2) < 0$
RECORDING INSTRUMENTS	
INTERCONNECTING TRUNKS	

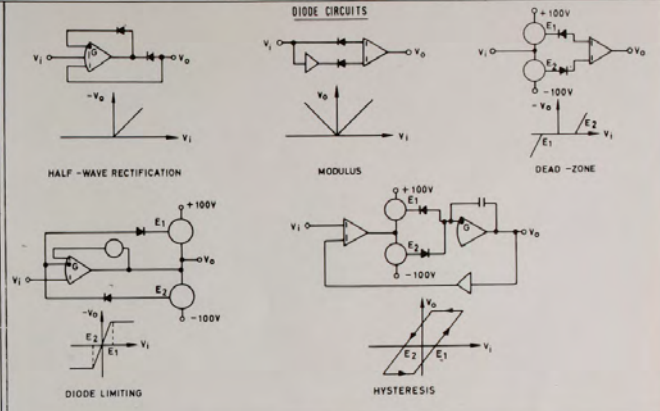
SYMBOL



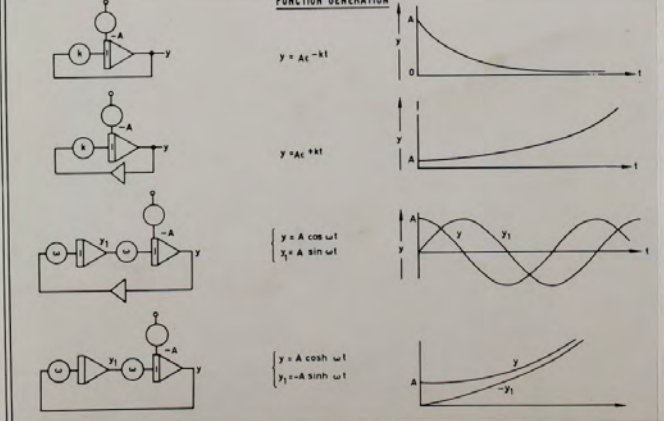
COMPUTING OPERATIONS



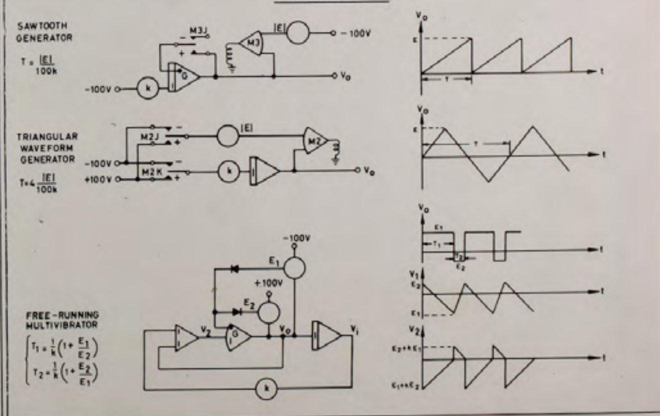
DIODE CIRCUITS



FUNCTION GENERATION



WAVEFORM GENERATION



MANUAL OWNERSHIP RECORD

BE SURE TO FILL IN BOTH SIDES OF THE SHEET, RETURNING THE RIGHT-HAND SLIP ONLY TO THE ANALOGUE COMPUTATION LABORATORY, EACH TIME MANUAL CHANGES OWNERSHIP. ONLY IN THIS WAY CAN IT BE KEPT UP-TO-DATE WITH THE LATEST AMENDMENTS

THE OLD OWNERSHIP RECORD MAY BE REMOVED CONVENIENTLY BY CUTTING RIGHT ACROSS THE PAGE ON MAKING OUT EACH TRANSFER SLIP. WORK FROM THE BOTTOM OF THE SHEET.

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