Title
CONSTRUCTION AND MAINTENANCE REPORT ON THE UCRL SYNCHRO DRIVEN DIFFERENTIAL ANALYZER

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Earl G. Sorensen

February, 1952

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Radiation Laboratory, Department of Physics
University of California, Berkeley, California

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PREFACE

The intent of this report is to give a general physical description of the analyzer; discuss the components and accessories in view of their theoretical and operational considerations; and to discuss electro-mechanical adjustments of critical components and methods of testing.

Presentation of the material consists of illustrations, diagrams, and data considered pertinent as a guide to continued useful service, or possible duplication of the UCRL Synchro-Driven Differential Analyzer. A report on problem solution and application of the analyzer to fit the limits of the analyzer elements is in progress by the Theoretical Group of UCRL and will be issued as a separate report. Construction and development of this analyzer was done under the auspices of the Atomic Energy Commission.

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CONSTRUCTION AND MAINTENANCE REPORT ON THE UCRL SYNCHRO DRIVEN DIFFERENTIAL ANALYZER

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SECTION 1

INTRODUCTION

A - Background

During the summer of 1951, UCRL used a differential analyzer constructed by Dr. A. N. Nordsieck of the University of Illinois. This machine employs the methods of integration conceived by Kelvin and Bush combining mechanical and electrical features to a distinct advantage. Results obtained at UCRL using the analyzer were so gratifying that plans were made for construction of a comparable instrument.

A construction report was submitted (compiled from available notes and study of the analyzer in use) consisting of details and information pertinent to construct such an analyzer. Constructional problems and improvements to be incorporated in the proposed analyzer were discussed in a meeting with Dr. Nordsieck. Construction started in June, 1951 and the completed differential analyzer was turned over to the Theoretical Group in mid December.

In order to arrive at a reasonable basis of design, literature of existing mechanisms was investigated,[1,2] features of the existing machine were discussed, and experience gained by our Theoretical Group in operating the Illinois analyzer was reviewed. Requirements predicted by use of the Illinois

1 Crank, J.: The Differential Analyzer, Longmans, Green, London, (1947).
2 Hartree, D. R.: Calculating Instruments and Machines, Univ. of Ill. Press Urbana, (1949).

analyzer indicated that at least eight integrators, six multipliers, four adders, and four plotting tables should be a minimum and since future requirements were rather indeterminate, a multiple of this ratio of components seemed reasonable if an instrument of increased size were contemplated. Further, it was deemed necessary that design should allow for additional components in the future without entailing a complete new design. Finally, it was decided that the differential analyzer would consist of twelve integrators, twelve multipliers, eight adders, four plotting tables, and normal accessories to utilize these components for maximum flexibility. Review of the literature disclosed that this choice of components was in line with the thinking of designers of existing as well as contemplated new construction, therefore, a reasonable conclusion.

B - Function

The differential analyzer is no substitute for the formal treatment of differential equations, but in the main its primary function is to evaluate numerical solutions of equations having no known formal solution. It can only evaluate particular numerical solutions of particular equations in which all coefficients have numerical values and for which numerical conditions are known and is, therefore, of more use to the practical rather than pure mathemetician. Essentially the analyzer discussed in this report consists of a number of integrating mechanisms employing the Kelvin-Bush principle of ball, disc, and lead screw to obtain the continuously variable rate of change method of integration. Shafts of selsyn-synchro motors are coupled to these elements of the integrators and by suitable patching of the selsyn motor electrical terminals, these integrators can be connected together so that the resultant assembly of components is constrained to solve any type of ordinary differential equation subject to the conditions previously stated.

SECTION 2

GENERAL PHYSICAL DESCRIPTION

a) Physical layout of the components integrated into one instrument presents many problems and since much original thinking had gone into the Illinois analyzer a "second guess" was deemed most advisable in using the best features of that machine and improving the design where possible. It was decided that the analyzer would consist of two units; each unit to consist of a suitable table, mounted on casters, of sufficient strength to support six integrators, six multipliers, four adders, two plotting tables, and necessary supplementary equipment. Figs. 1 and 2 show the completed instrument and one unit, respectively. Each unit is 32 inches wide, 54 inches long, and 45 inches high. Each unit is equipped with casters and may be moved over reasonably level surfaces from one location to another. Adjustable rigid casters are located at the plug-board end for leveling the table surface and to provide stability at the end where the plugging operation is done. Knee-hole table construction, table height, as well as arrangement of the control and console panel, were chosen to reduce operator fatigue where possible.

b) Enclosure of components was necessary for the protection of operating personnel as well as protection of the mechanisms from dust, rust, and damage. Components mounted on the top table surface of the analyzer include six integrators, two plotting tables, and two independent counters. Integrators, located under the Lucite cover, are protected but visible to the operator to permit observation of the elements during initial problem set-up. These are numbered one through six as viewed from left to right (Fig. 2). Numbers 5 and 6 employ differntial selsyns to drive the lead-screw, as do two spare integrators which may be used as remote spare components for each analyzer

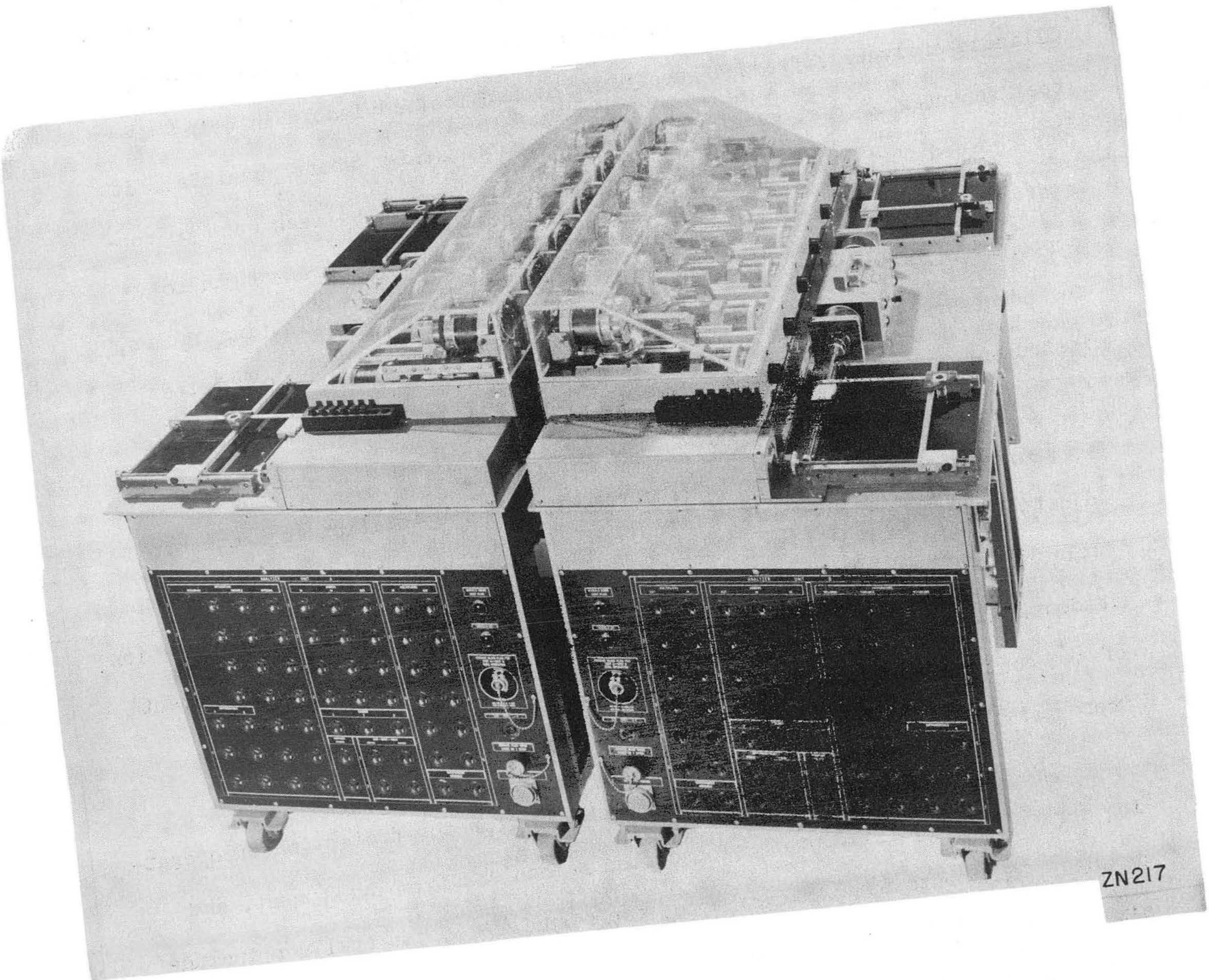


Fig. 1

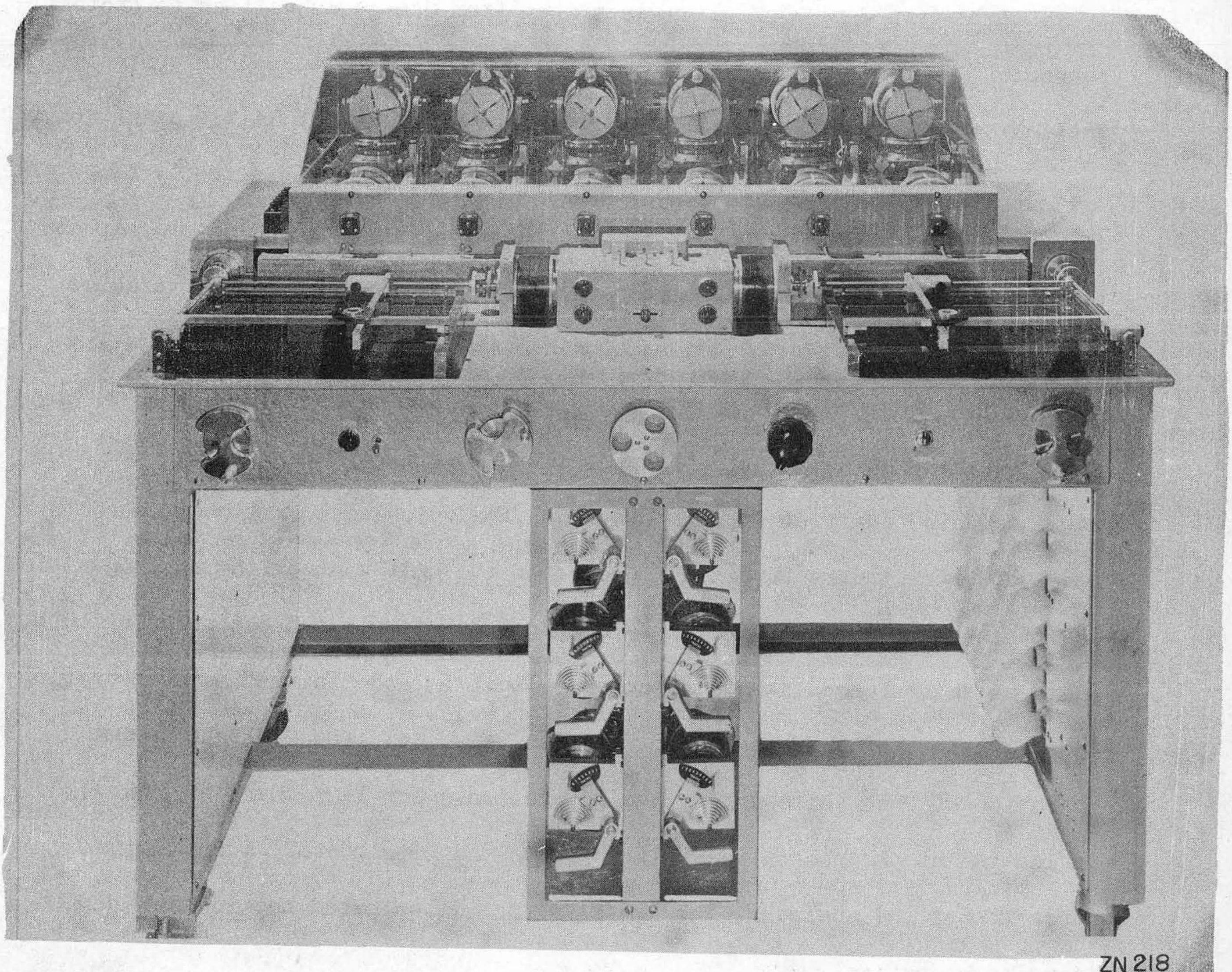


Fig. 2

unit. The spare integrators may also be used to replace any component integrator when effecting repairs or maintenance. Multipliers and adders are protected by locating them under the table top. The multipliers are framed by an angle-iron rectangle to protect them from damage as well as to protect personnel against electric shock. Four adders are located on the central T-section member, behind the multipliers, since they require little attention, they are placed accordingly. The analyzer control panel is directly above the multipliers. Mounted on it are: three cranks; power indicator lamp and switch; the independent variable crank wheel; and the independent variable selsyn drive-motor speed and direction controls. Both units of the analyzer are identical when viewed from the front, as shown in Fig. 2, and may be operated as separate units at different locations. They may also be used as a combined large analyzer in dual operation, in which case only one control panel operates the combination. Choice of the unit controlling dual operation is optional and may be selected by means of a suitable cable connecting both units at their respective plug boards. "Unit A" and "Unit B" have their plug boards at the left and right ends respectively, to allow for back to back operation of both units during dual operation. The lamp board of each unit is located at one end of the unit opposite the plug board. During normal operation of the analyzer, the lamps are not illuminated but indicate conditions of operation.

c) All components are assembled separately and electrical connections from them are made to the main frame of each unit by means of Cannon connectors. This permits removal of components for servicing as well as expediting construction and adjustment after construction. Separate assembly and disassembly by means of cable connectors is also an advantage when shipping the analyzer by common transportation methods. Fig. 3 is a view of the multipliers on one

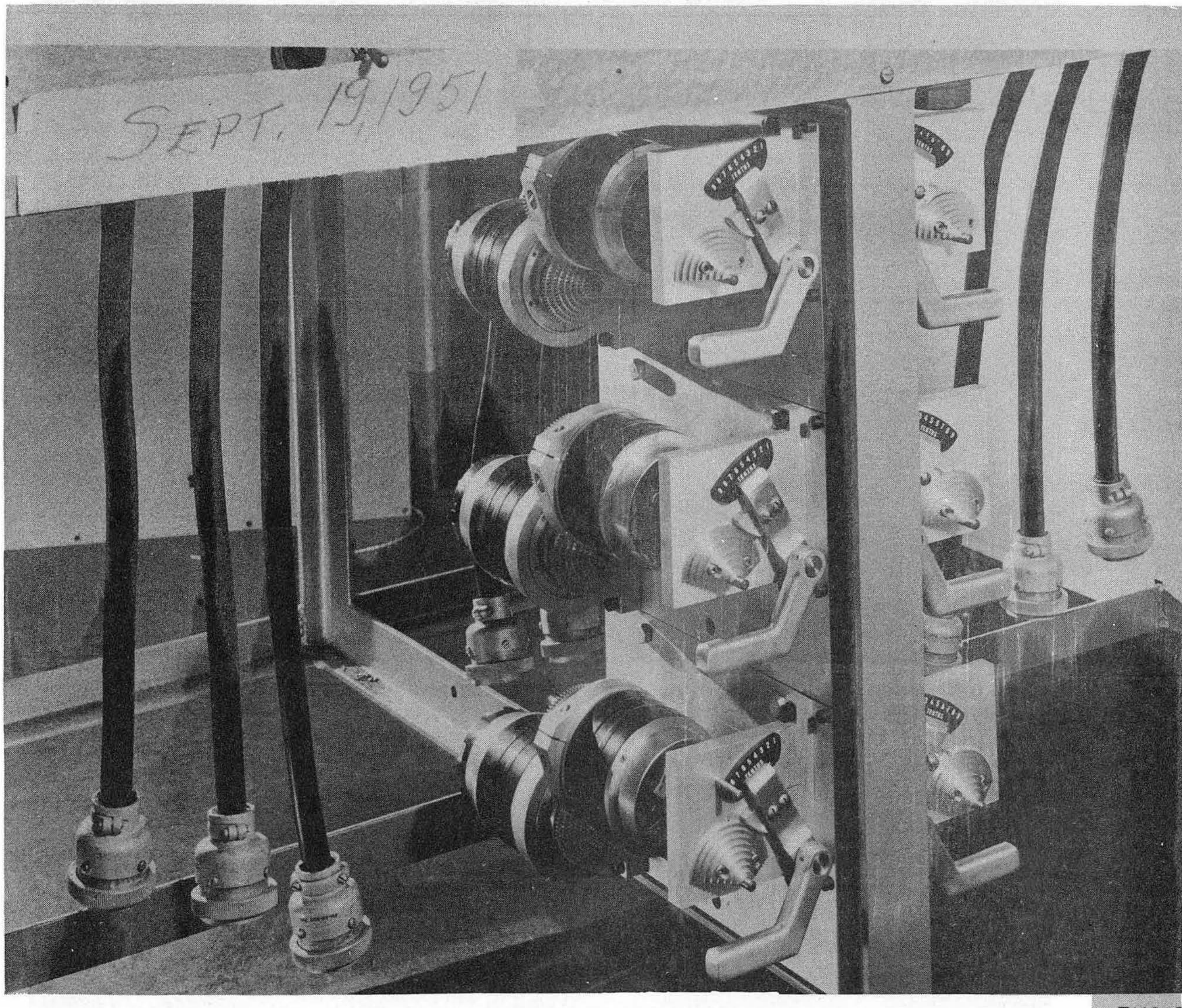
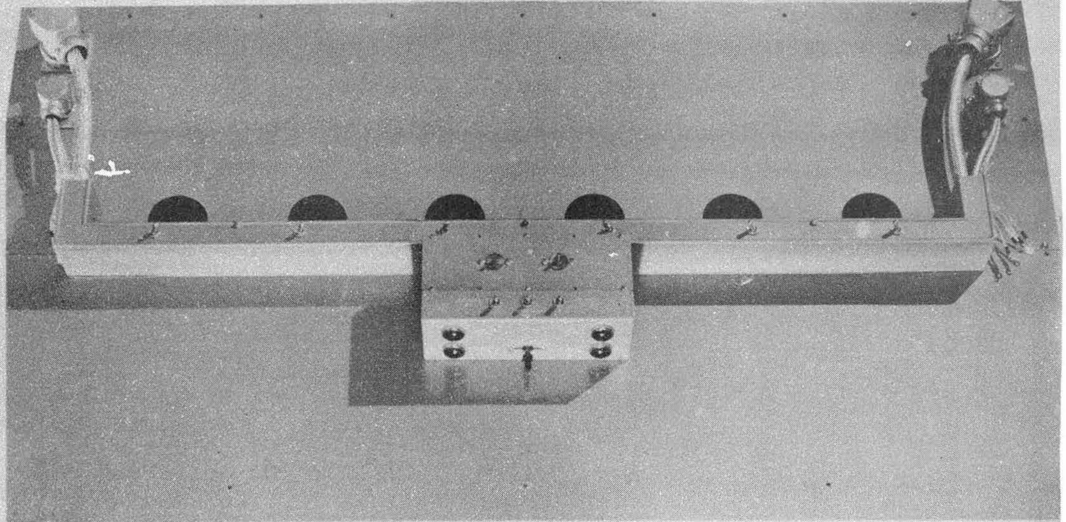
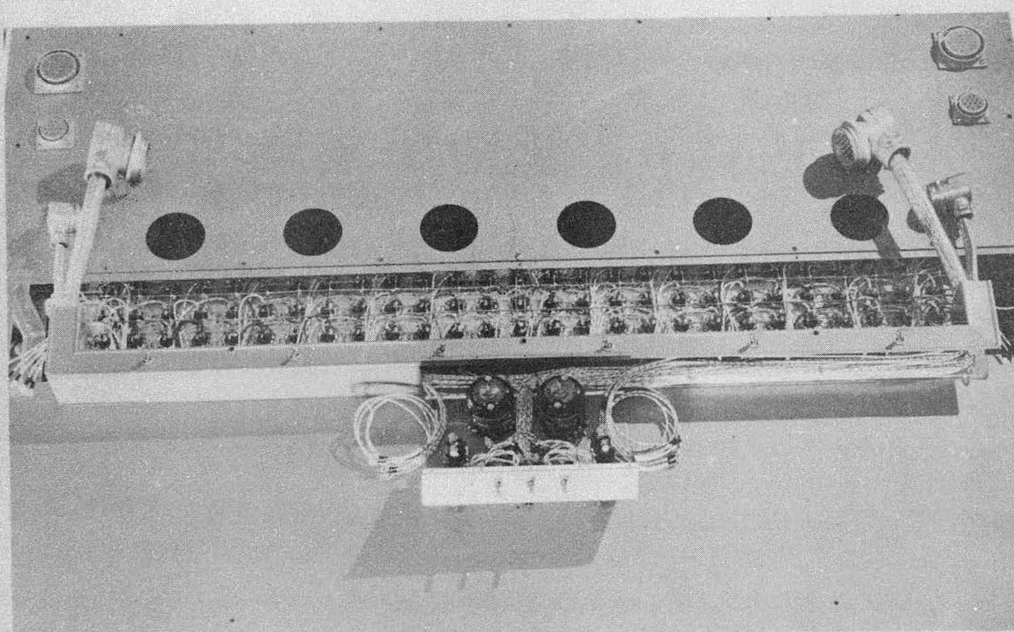


Fig . 3





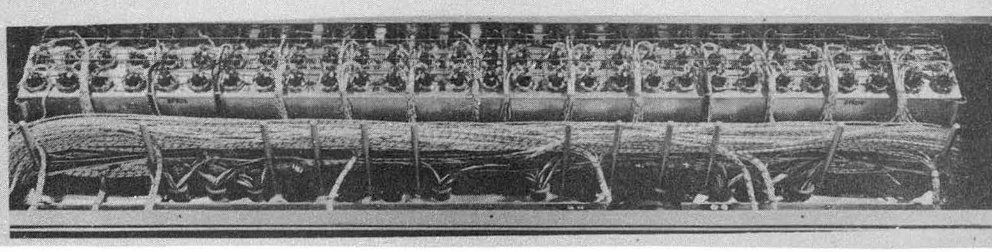


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Fig. 4
Fig. 5
Fig. 6

unit; cables and connectors for the integrators are shown disengaged. Figs. 4, 5, and 6 show a unit table-top with integrators, plotting tables and all protective enclosures removed, illustrating the method of gaining access to internal wiring of capacitors and control panel as required for maintenance or replacement of I.V. drive belt. Cable plugs connecting the console and plotting tables are attached to the front half of the analyzer table. Removal of these plugs and a few machine screws permits the front half of the table-top to be pulled forward. Normally, the plotting tables rest on this front section and it is not necessary to remove the plotting tables to gain access to this part of the analyzer. Figs. 7 and 8 are internal views of the plug-board and lamp-board wiring, respectively, showing the means of enclosure and availability of the equipment. This completes the general physical description of the analyzer. The section to follow discusses each component of the analyzer in more detail, correlating the theory and function of these elements.

SECTION 3

ANALYZER COMPONENTS

A - Integrator

a) Fig. 9 shows a simplified diagram of an integrator. The process of integration is performed as indicated on the diagram. Normally, the differential equation to be solved is broken down into integrals; these integrals in turn are translated into fundamental units of the integrator elements which perform the actual operation of integration. Integration is performed by a continuously variable gear ratio, passing from positive through zero to negative values. Thus, if shaft A (variable selsyn) is arranged to drive a second shaft B (integral selsyn) where the wheel and disc point of contact is located

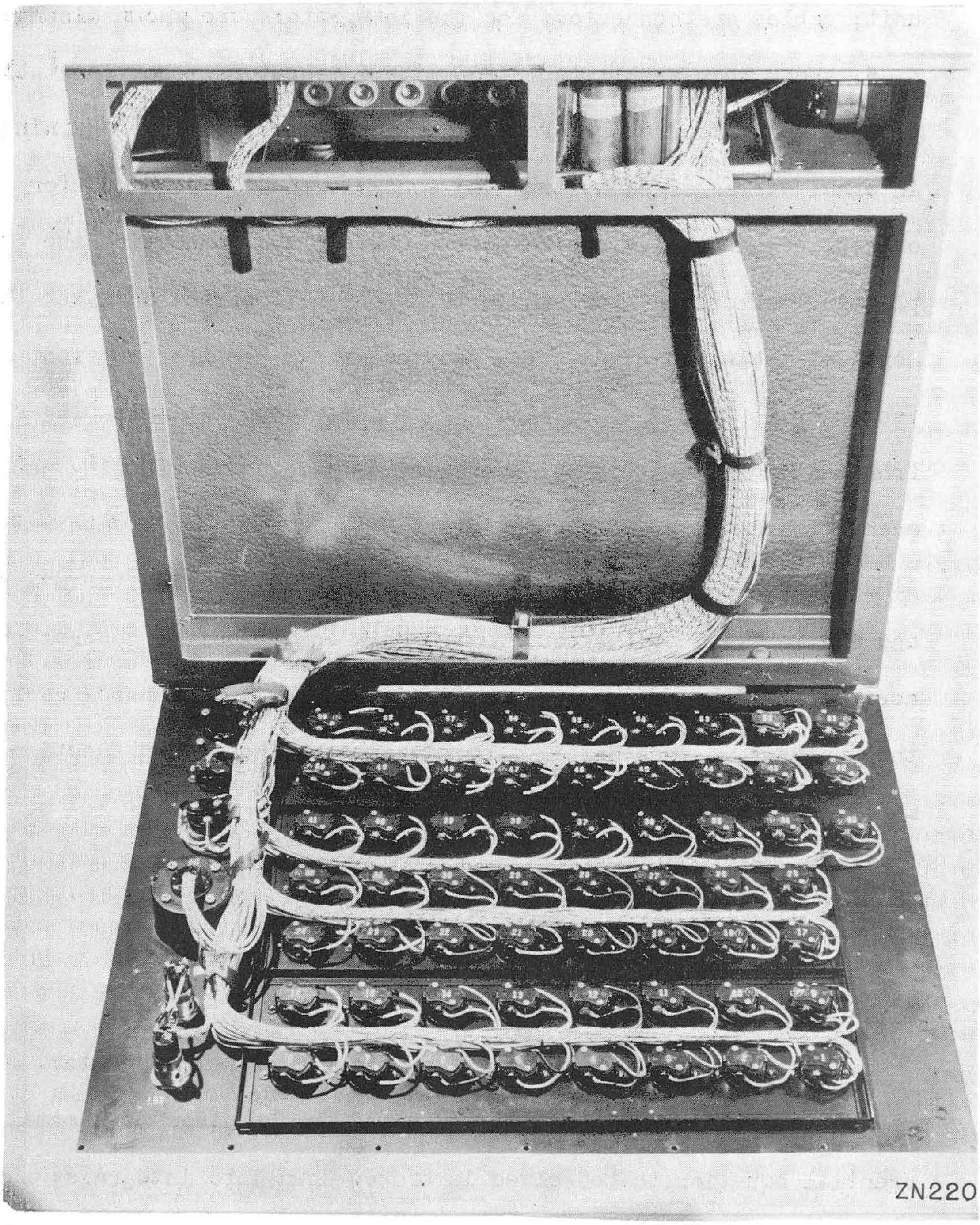

Fig. 7

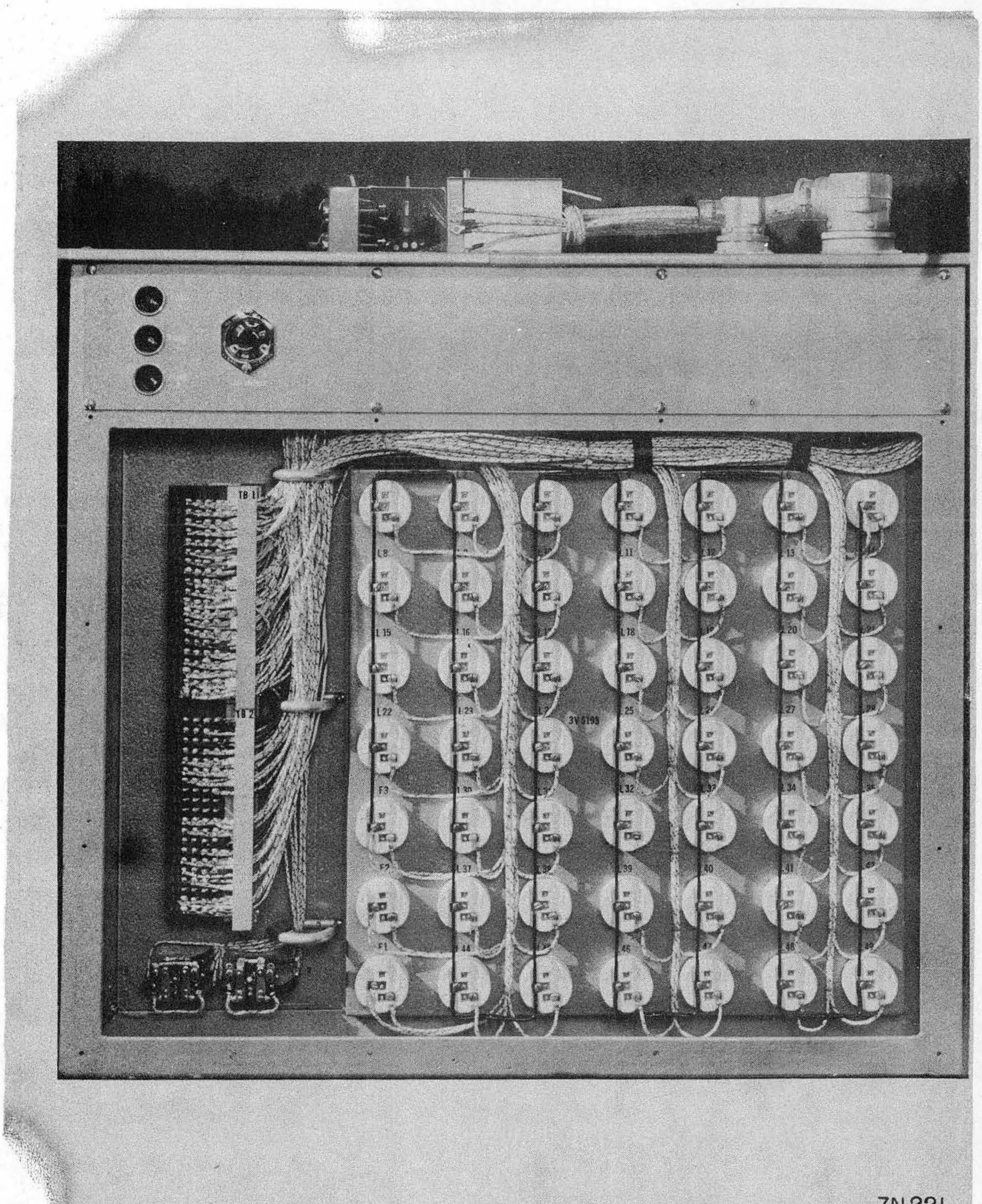

Fig. 8

INTEGRATOR

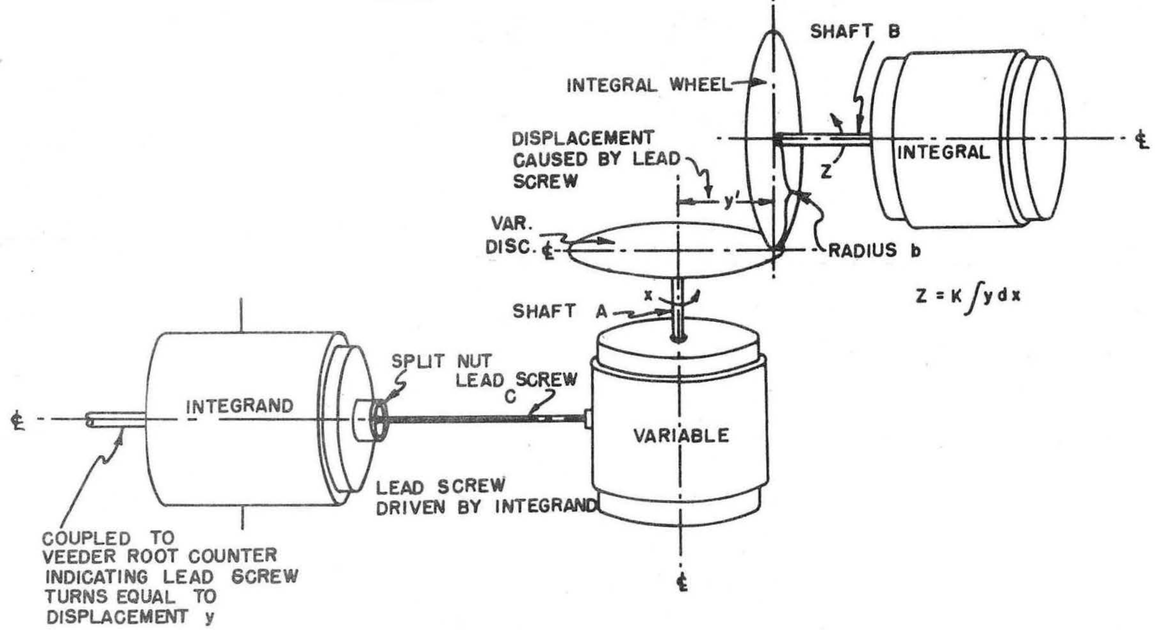

FIG. 9

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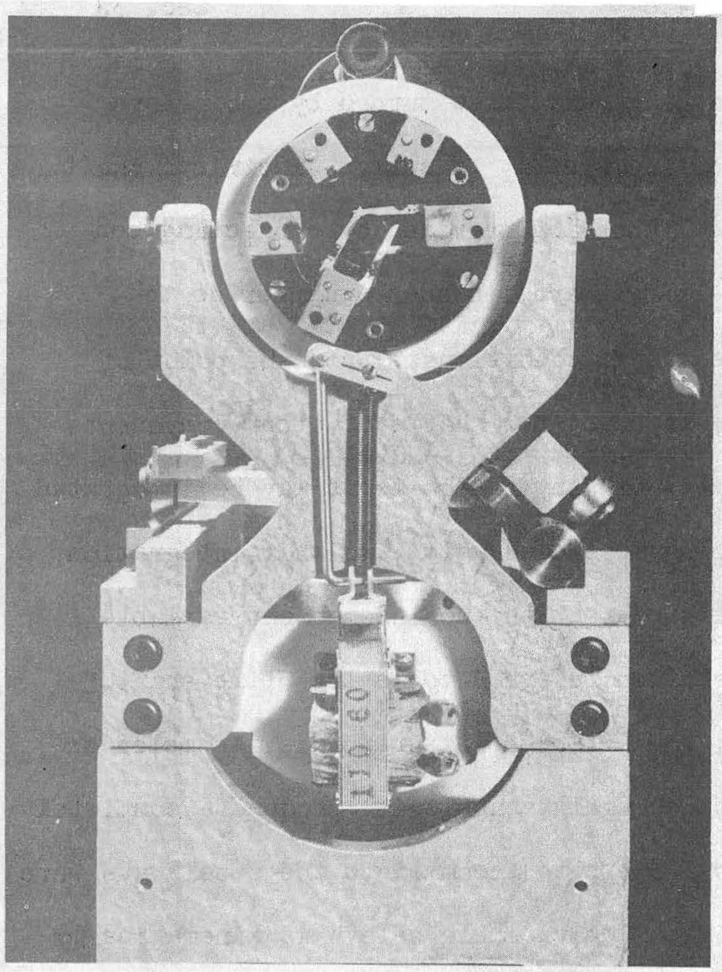
from the center of the disc by displacement y', a small rotation of shaft A moves the disc through a small fraction of a turn dx. The integral wheel will thus rotate through $y'dx/b$, where b is the radius of the wheel, provided there is no slip. Displacement of the lead screw C, can be varied by electrical rotation of the integrand selsyn rotor shaft; therefore, this shaft may be considered as the ratio shaft. Total rotation of the integral wheel z is equal to $k \int y\,dx$, where k is the integrator constant determined by the pitch of the integrand lead-screw and the radius of the integral wheel.

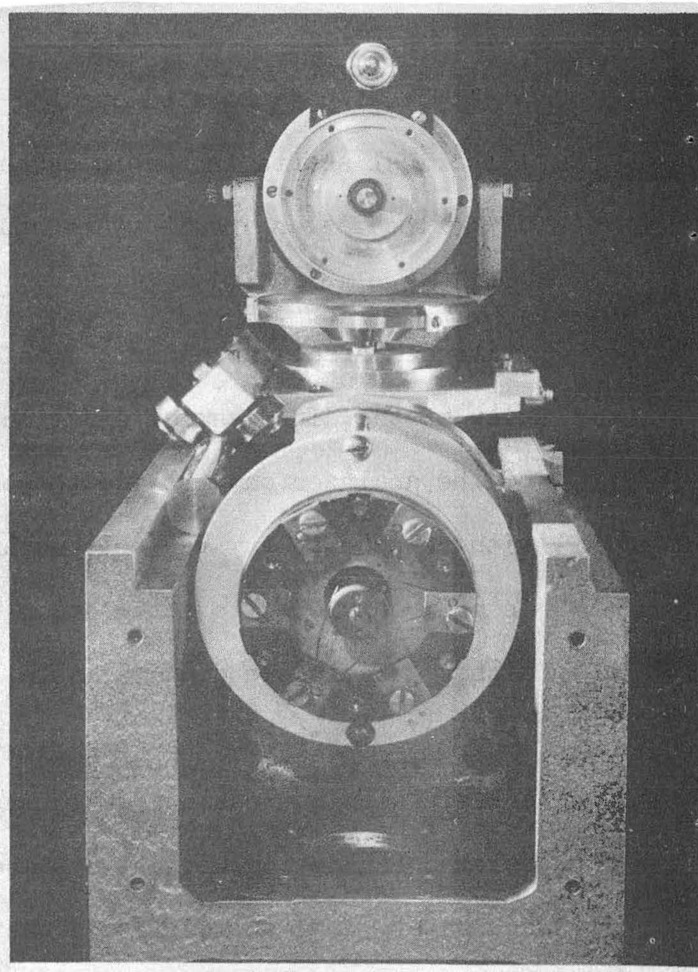
b) It is necessary to express all quantities in terms of selsyn shaft rotations so the expression for the rotation of the integral wheel can be obtained in a useful form. The number of turns, y, of the integrand shaft C, to produce a linear displacement, y', of the variable disc is given by $y = y'/P$, where P is the pitch of the integrand lead-screw. Since the variable selsyn shaft drives the disc directly, substituting for y' in the expression for rotation of the integral wheel, shows that the rotation of the output shaft for an integrator unit is given by $P/b \int y\,dx$. The term b/P is referred to as the integration constant k'; therefore, the expression of the output shaft of the integrator is $Z = k \int y\,dx$, where $k = 1/k'$. For the analyzer described, the integrator constant was designed to be 50; all 14 integrators are within 0.1 percent of this value. Pitch of the integrand lead-screw is 1/30 inch and the integral wheel diameter is 3-1/3 inches. Considering the variable selsyn as the input shaft and the integral-selsyn as the output shaft, if the displacement of the wheel from the center of the disc is constant at 50 turns of the integrand lead-screw, the input and output shafts perform the same number of rotations in a given time, or, the integrator could be said to have a gear ratio of one to one. This ratio is the maximum operating range of the integrators and is set by the diameter of the disc, and displacement of the lead-screw. Electro-mechanical means of limiting displacement, protecting elements from damage, and warning the operator are incorporated as discussed later in detail. Displacement of the disc by varying the lead-screw displacement causes a change in the input shaft ratios and may reverse the rotational direction of the output shaft. Means of determining the lead-screw turns and the zero position of the integral-wheel are necessary.

c) A Veeder-Root counter (integrand counter) attached to one end of the integrand-selsyn shaft indicates the number of turns the lead-screw is displaced as a consequence of shaft rotation. The counter is a 3-digit 0-100 unit, direct reading to one tenth of shaft revolution. Zero counter reading is set so that the integral-wheel is in contact at the center of the variable-disc, which extends the lead-screw out of the integrand-nut about half of its length. Rotating the variable-disc causes no rotation of the integral-wheel when the zero point of contact is correctly adjusted. Counter readings from 0 to 50 are considered positive in sense; readings from 100 to 50 are considered negative. In this manner an algebraic sense is assigned to shaft rotation of the integrand selsyn. Counterclockwise rotation, of all elements of the integrators, when viewed from the shaft end of the motor, is assigned positive rotation and the control wires of each selsyn are so phased at the plug board. Readings of displacements of the variable discs determine the accuracy with which initial settings may be made or taken at any point in the solution of a problem; therefore, the accuracy of this setting is a major factor in determining the overall accuracy to be expected of the analyzer. It might be mentioned that in order for a particular integrator to operate, it is necessary that the disc be rotated and the displacement screw turned by two selsyn electrical shafts in the interconnecting system. A selsyn electrical shaft is defined as an imaginary mechanical coupling provided by connecting control wires of a given selsyn at the plug board, in such a manner as to drive other selsyns under controlled servo conditions. From the point of view of the differential equation, since any two shafts of other components of the analyzer may provide these motions, any of the terms may be integrated with respect to any variable occurring in the equation, so that integration is not restricted to integration with respect to the independent variable alone. The independent variable is often referred to as the "time shaft."

d) Referring to Figs. 10, 11, and 12, each integrator is assembled on a basic aluminum casting which was thoroughly annealed to produce a completely relaxed foundation without stresses. Steps to accommodate the steel ways were accurately gang-milled in the casting. The variable selsyn is kinematically mounted to roll on these ways as may be seen. A second casting in the form of a double yoke supports the integral selsyn mounting ring by two pivot bolts; also, the tilt solenoid and linkage are supported by this casting (Fig. 10). Mounted in the internal web of the casting may be seen the integrand selsyn. This mounting is arranged to clamp the selsyn motor in position but allow for the necessary adjustments. Note in Fig. 11 that the integrand selsyn shown is a differential type which required a slip-ring and brush assembly not provided on the original unit. Comparison of the wire terminals on the motors in Figs. 10 and 11 discloses the difference between the two selsyn types. Several features visible in Fig. 12 are worthy of note.

e) First, notice that the integrand lead screw is disengaged from the mating drive nut. This nut is split into two sections; one section is fastened rigidly to the shaft hub; the other is spring loaded and adjustable so





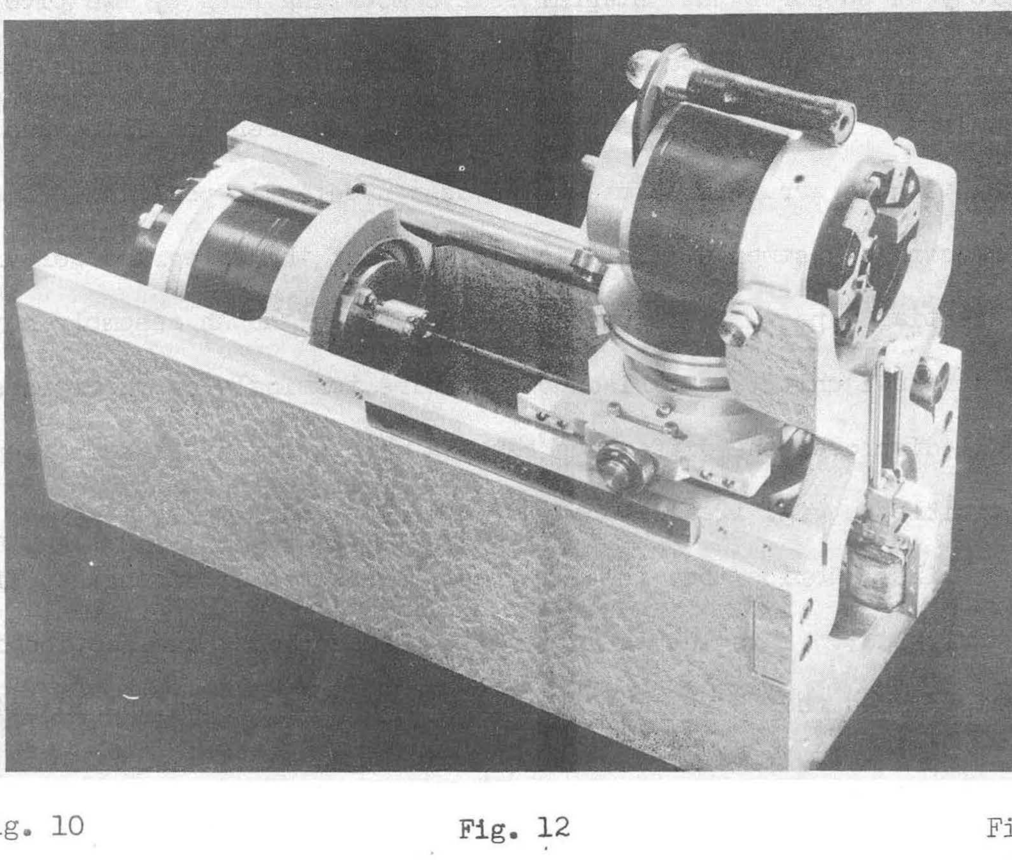


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Fig. 10 Fig. 12 Fig. 11

that minimum backlash is obtained. Both ends of the lead-screw have the threads relieved. This feature protects the lead-screw assembly from damage in the event that the electrical circuits fail to stop the lead-screw drive from over-running normal displacement limits.

f) Fastened to the variable selsyn mounting plate may also be seen an adjustable beam. This beam has an adjustable pawl located at either end for setting the displacement limits over which the variable assembly travels. A roller, bearing against the beam, actuates two microswitches at different intervals as it rides up on the pawl. One microswitch operates the limit circuit, the other operates the tilt circuit.

g) Another feature to be noted on Fig. 12 is the wear plate mounted on the variable turntable, referred to as the "variable disc." This disc is clamped to the turntable by three clamping dogs -- a necessary feature to allow the disc to be removed and reground. The surface of the variable turntable was machined normal to the shaft axis after being assembled on the selsyn, using the selsyn motor as the power drive. This method provides a means of obtaining a reference plane on which to secure the wear plate. Thus, wear occurring on the disc, caused by the integral wheel, may be removed by regrinding the disc.

h) The disc hardness was obtained by pack-hardening and drawing to Rockwell 60; the reasoning behind this being that wear should be confined to the greatest degree upon the wear plate which can be reground. Any considerable wear occurring on the integral tire upsets the integrator constant, requiring a new tire; therefore, the tire was hardened to Rockwell 64. Since the lead-screw pitch and integral wheel tire radius determine the integrator constant, these elements are made to very close tolerances and represent a major portion of the total cost of the integrator. Before we look into the details of these elements of the integrator it is better that we discuss the electro mechanical mechanism previously referred to as the tilt circuit.

i) Simply stated, the tilt mechanism merely disengages the integral wheel from the variable disc. Functionally, the mechanism is operated by the operator at his option, or automatically operated by the interlocking circuits of the analyzer as a "fail safe" or analyzer protection device. As a "fail safe" device, the tilt mechanism protects the integral wheel from damage in the event the variable disc is displaced far enough to allow the wheel to run off the surface of the disc. Such displacement of the disc invalidates the problem solution as well as previous adjustments of the integrator, so must be avoided.

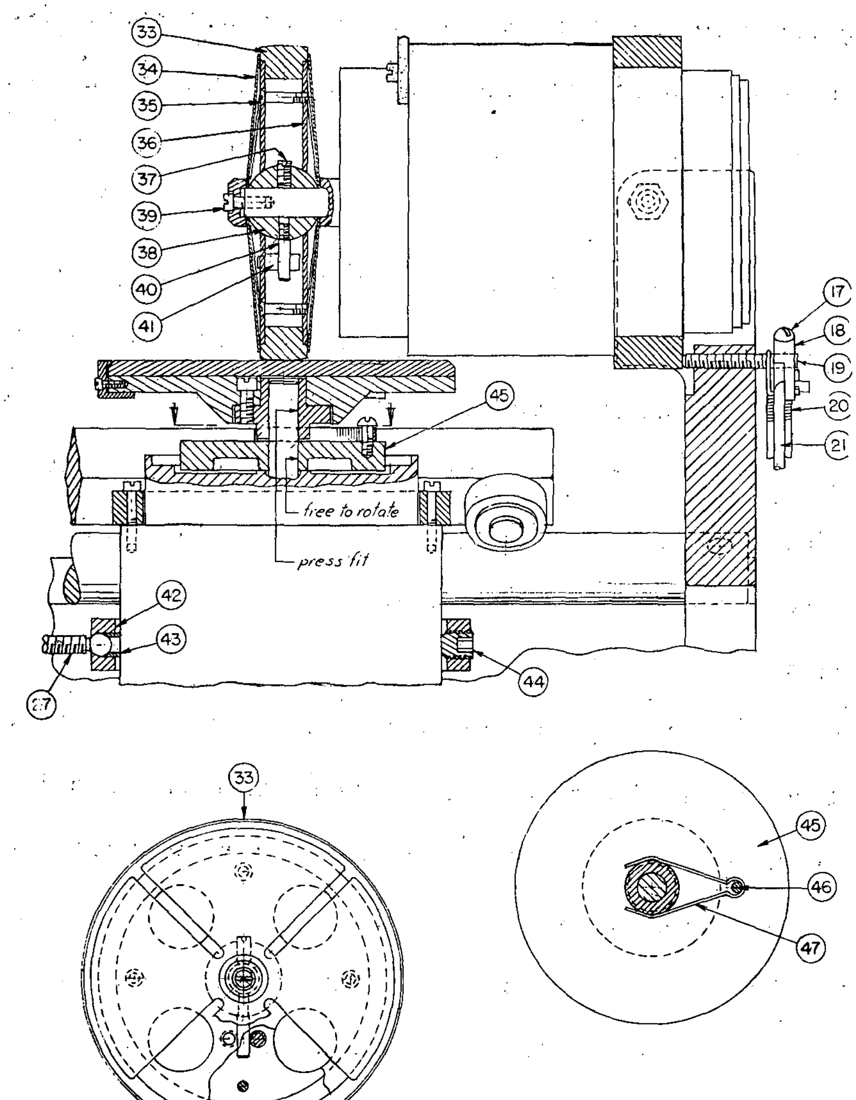
j) Disengaging the wheel and disc, as done by the operator, is necessary when initial setup of a problem is performed. Setting the counter of the integrand element means that the variable disc must not engage the integral wheel during this displacement operation; therefore, a means of control to effect the "wheels up" and "wheels down" operation is necessary and is provided. Discussion of the electrical circuits covers the operational method and is given later; action of the tilt mechanism will now be described.

k) Fig. 10 shows the tilt mechanism consisting of an A.C. operated solenoid with the armature connected to a tilt rod and tilt arm. Displacement of the armature operates the rod and arm translating vertical motion of the armature into circular motion about a pivot set-screw to which the arm is clamped. The pivot set-screw bears against the bottom of the integral support ring in such a manner that its right hand threading action causes the integral selsyn to tilt on its pivot bolts, thus raising the extended shaft of the integral selsyn through amall vertical displacement. This small vertical displacement raises the integral wheel from the variable disc when properly adjusted. Displacement of the armature to raise the integral wheel is affected by means of a steel coil spring which is cut to a length so that in its near relaxed position it displaces the solenoid armature as shown. Energizing the solenoid operates the armature which in turn tensions the spring, thus operating the linkage to lower the integral wheel into contact with the variable disc. De-energized, the spring tension displaces the solenoid armature which means that when the analyzer is not in use, and the power is off, the integrator wheels and discs are not in contact.

l) Figs. 10, 11, and 12 are typical views of an integrator in state of assembly. Details of mounting the integral wheel, limit and tilt protective switches, and integrand counter are shown in Figs. 13 and 16. The unique design of the integral wheel is of major importance and contributes a great deal to the successful operation of this type of integrator. Salient advantages of the spherical wheel design are as follows:

1. The contact radius is constant.
2. Slight wheel wobble does not impair kinematic relations.
3. The lead-angle of the wheel in contact with the disc is self correcting, thus producing a minimum of slip during reversal of the wheel when passing through zero.

m) With reference to Fig. 13, all parts of the wheel are exposed. A 3/4-inch brass ball (38) is locked to the selsyn shaft by a set-screw (37). Two discs (36) are clamped to the tire (33) by means of four screws (35) which by adjustment of their tension cause the discs to diaphragm against the surface of the brass ball. A stainless steel straight pin (40) pressed into the ball, normal to the axis of its shaft hole, is constrained by two pins (41). Thus, the wheel assembly is restrained to rotate with the selsyn shaft but free to rotate through a small solid angle about the axis of the selsyn shaft. Two


33
34
35
36
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39
38
40
41
17
18
19
20
21
45
free to rotate
press fit
42
43
27
44
33
45
46
47

Fig. 13

springs (34) engage each quadrant of both sides of the wheel. They supply the required restoring force necessary to maintain the wheel normal to the axis of rotation when the wheel is raised from the variable disc. Design of the tire (33) predicated the foregoing means of attaching it to the selsyn shaft. The tire is a generated central section of a sphere, and its mounting is such as to provide all the advantages of a free rolling ball but retaining the necessary restriction required to rotate a shaft.

n) Before continuing with the description of other components it is worthwhile to mention the method of fastening the integrand lead-screw to the variable selsyn motor frame. A 1/4-inch brass ball is pressed on one end of the lead-screw. This end of the lead-screw fits into a conical socket of the lead-screw clamp ring, part (42) Fig. 13. A tubular spacer (43) compressed between the lead-screw ball and selsyn frame prevents the lead-screw from turning. Set-screw (44) and two others located 30 degrees either side of it locate the clamp-ring and lead-screw.

B - Plotting Table

a) Necessary components to obtain graphical solutions of differential equations are the plotting tables. Of necessity, they are made left and right handed to fit in the space available. (See Figs. 1 and 2.)

b) Plotting tables have a two-fold function. They may be operated as input tables to feed information into the analyzer; or be operated as output tables producing a graphical relation between any two shaft rotations.

1) As an input table, the curve of a function $f(z)$ of some variable z may be fed into the machine. The curve may represent a function generated from the analyzer as cited above, or empirical data tabulated from experimental phenomena. In any event the interconnecting system can be arranged so that the

operator, sighting through the index of the plotting table carriage, supplies the ordinate information by cranking a selsyn (crank) in such a manner as to maintain the index on the curve, while the analyzer is automatically supplying the abscissa value. Only functions of a single variable may be handled in this manner and then they must be properly scaled to conform with limits over which the various components operate.

2) Two functions may be plotted on separate axes in which case the components supplying the functions may come from any element or component of the analyzer. In this case the graphical result may well be the information desired of the differential equation under investigation. The component is then operating as an output table.

c) Each selsyn is coupled to a lead-screw through a flexible ball-and-finger coupling. A knurled wheel fastened to the selsyn shaft, and one fastened to the lead-screw, separated by the coupling, allow for slight adjustment when setting initial conditions; that is, by restraining the selsyn shaft with one knurled wheel, and turning the other knurled wheel, fine adjustment of the lead-screw displacement is obtained.

d) Beams which position the carriage are fastened to brass blocks containing cylinders through which the lead-screws are engaged. Lead-screws are engaged in the cylinders by means of a half-nut and an unthreaded mating plug. One end of the cylinder is fastened to the half-nut; the mating plug is spring loaded in the cylinder so that the plug and half-nut engage the lead-screw under pressure of the spring. The cylinder being at right-angles to the lead-screw is free to rotate in the block but the fitting tolerance is such as to produce minimum back-lash between the beam and lead-screw. Black bakelite buttons evident on the beam block (Fig. 1) are placed so that finger tip pressure releases the beam block from the lead-screw, and the beam may be traversed along the guide way for positioning the index. Thus, the plotting table index can be set roughly to a given point along one of the coordinate axes by traversing the beam with the half-nut disengaged; fine adjustments can be made to the given point, employing the lead-screw knurled wheels. Excursions of the beams are limited at each end of their travel by a mechanical linkage, which, when contacted by a beam block actuates a microswitch, opening the electrical drive circuit. Limits are set to protect the lead-screws and to fix the area graphically recorded by the pen.

e) The beam block is guided along precision ground hardened steel ways by means of the clamping action of three roller bearings mounted horizontally to the beam block. Right angle stepped grooves are ground on opposite sides of the ways in which the bearings roll. Sliding friction between the edge of the bearing and the horizontal footing of the groove is minimized by reduction of contact area.

f) Design of the index carriage is such that the carriage can be removed from the beams, facilitating index cup changing and for removing dust and accumulations tending to cause the carriage traverse to be impaired. Gravitational force holds the carriage in contact with the beams and since translation of the beam action to the carriage is done by shearing action of both beams, it is important that both the beams and carriage slots be kept clean.

g) The index cup fits into the carriage by virtue of a very slight press fit and may be removed as necessary. One end of the index cup is closed by a thin plexiglass disc; in the center of the disc is a small drilled hole which serves as a "peep sight" when the index is used for curve following. A penholder employing a LeRoy lettering pen, may be inserted into the index cup without removing the carriage. The pen holder is designed to fit freely but accurately in the index cup thus allowing the operator to use the "peep sight" for initial adjustment before the pen is placed in position, therefore, inking of the coordinate paper may be done accurately and neatly.

h) LeRoy No. 3233-00 pens are held in the pen holder by a friction fit. The holder allows for movement of the pen cleaning pin but does not permit the pin to become disengaged from the pen. Cleaning pins as well as the complete pen are easily replaceable and obtainable. Fountain pen ink, of the non-gumming type is used and found very satisfactory. India ink may also be used, but it is not recommended due to its greater viscosity and tendency to clog.

i) Keuffel and Esser Company 7 x 10 inch No. 358-11 paper is used on the plotting tables. This paper is engraved 20 lines to the inch and since the lead-screw pitch is 1/20 of an inch, one turn of the lead-screw traverses one space of the coordinate paper. The displacement ratio of the integrand lead-screw to the plotting table lead-screw is not as convenient to scale as it might be, but physical and mechanical compromises made the choice necessary.

C - Crank

a) In our discussion of a plotting table, used as an input table, we referred to the use of a crank selsyn as a means of manually operating one axis of the plotting table so that the index followed the function. Generally the problem is arranged so that some function of the analyzer drives the abscissa axis selsyn, and a crank operated manually by the operator drives the ordinate axis selsyn. Three cranks are located on the control panel, any one of which can be patched to achieve this end.

b) Each crank is directly coupled to a selsyn motor/generator. Located on the selsyn shaft between the crank plate and control panel is an adjustable collet which may be used to lock the shaft from turning. A fraction of a turn of the knurled wheel tightens the collet nut and locks the selsyn rotor. This locking feature provides a means of supplying excitation voltage of zero rotation to any differential selsyn. Excitation voltage of zero rotation in this sense is a voltage obtained from the output stator winding of a selsyn motor/generator having its input rotor winding locked so that the input and output voltages are fixed in phase position.

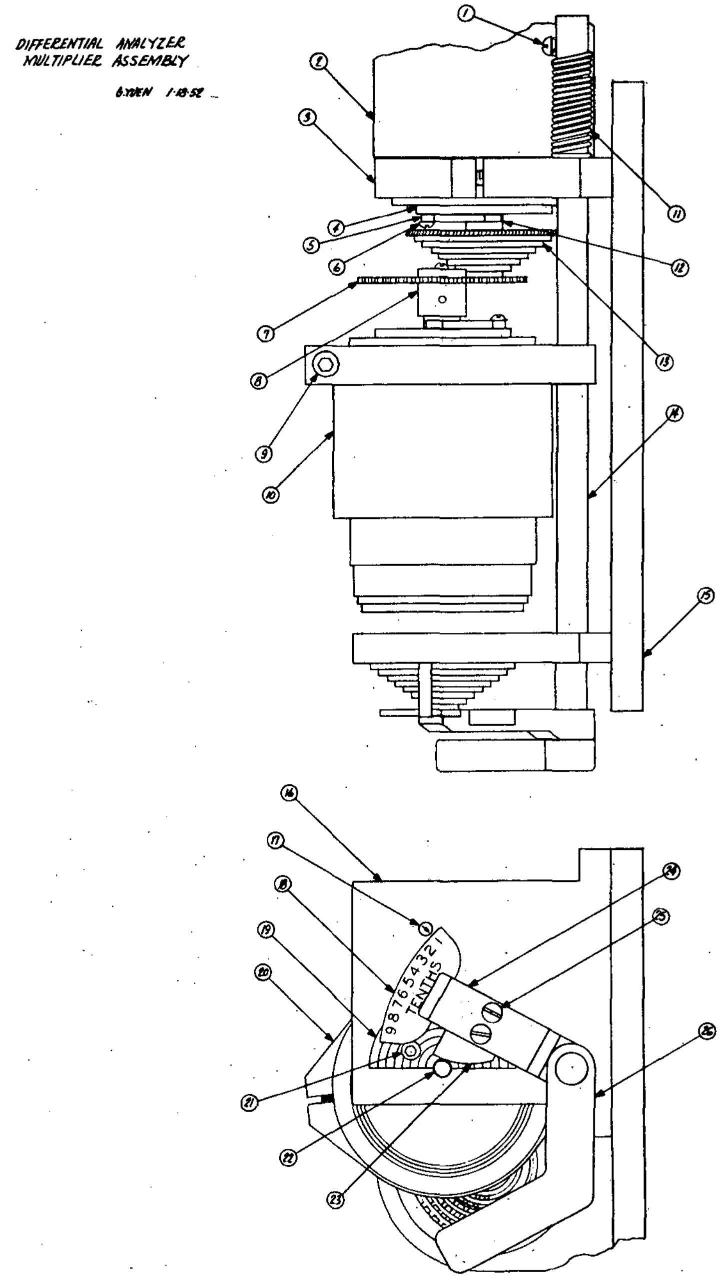
c) On each unit of the analyzer there are two integrators employing a differential type selsyn as the integrand element drive. We recall that the integrand element is considered as the ratio shaft of the integrator, but if the integrand employs a differential selsyn having two windings which may be connected to two separate controlling shafts, it then has two ratio shafts. If two functions, translated to electrical shaft rotations, are connected to the differential integrand input circuits, the integrand selsyn shaft will rotate as the sum or difference of these input functions, depending upon the phasing of their input connections. Under some conditions of operation it is necessary to use a differential integrand, but have only one function to integrate. This still requires that both windings be excited, one by a voltage of zero rotation and the other by a voltage from the electrical shaft being integrated. The locking feature of the crank provides a means of supplying the first voltage; the other voltage is provided from some component in the interconnecting system. Provision is thus made on each analyzer unit to operate integrators No. 5 and 6 and one input plotting table by means of the available cranks.

D - Multiplier

a) It is requisite that all displacements of the plotting tables and integrators be confined to their available working areas; because of this it is necessary to reduce all numerical coefficients to ratios or scale factors of the independent variable shaft revolutions. Many problems are of a research nature such that a priori determination of scale factors is not always possible, and must be arrived at by "trial and error" manipulation to obtain the proper conditions. Considering the independent variable as an electrical shaft, its rotation can be connected into the inter-connecting system so that it drives the system as a prime mover. Some of the components in the system may require a reduction ratio of the revolutions turned by the independent variable, in order to satisfy the numerical coefficients, or scale factors of the problem. This reduction ratio or scale factor can be obtained through the use of constant multipliers, referred to as multipliers.

b) Each multiplier is an arrangement of spur gears, connected to two selsyn motor/generators in such a manner that the ratio of their input to output electrical shafts may be easily changed by the operator. With reference to Fig. 14, the driving or input selsyn (10) has an 80 tooth 32 pitch gear (7) fastened to its shaft. Fitted to the driven (2) or output selsyn shaft is a conical nest of nine 32 pitch gears (13). These pitch diameters are selected to obtain a speed reduction of one-tenth to nine-tenths of the driving shaft. Both selsyns are assembled on a vertical mounting plate (15); the driven selsyn is located below and slightly behind the driving selsyn; the driving selsyn is clamped to a bracket (9) which in turn is pinned to the multiplier shaft (14) in such a manner as to permit engaging the gears of both selsyns.

c) The multiplier shaft may be rotated and displaced longitudinally in its bearings. Rotation of the shaft causes the driving gear to be raised



DIFFERENTIAL ANALYZER
MULTIPLIER ASSEMBLY
G.YUEN 1-18-52
9 8 7 6 5 4 3 2 1
TENTHS

ZN 222

Fig. 14

through an arc sufficient to clear the diameters of all gears mounted on the driven selsyn shaft. Displacement of the shaft allows for selection of the desired gear ratio. Manual rotation and displacement of the multiplier shaft is accommodated by an index handle (26) which has mounted on it an index arm (24), finger (23), and indicator plate (18).

d) A stepped half cone properly mounted on the multiplier front plate (16) serves as an index (19). Steps generated on the cone correspond to spacing between and pitch diameter of gears making up the conical gear cluster. The fiducial point of any gear setting is adjusted so that when the Lucite index finger rests on an index step, the gears are properly engaged and the ratio is indicated by a pin (17) adjacent to the outside arc of the indicator plate. Gravitational force acting on the driving selsyn together with spring loading (11) of the multiplier shaft supply the restraints necessary to maintain stability of a ratio setting.

e) All parts fastened to the multiplier shaft are done so by means of taper pins and Allen head set-screws. Gear clearance is set by two adjusting screws (25) which allow for proper positioning of the Lucite finger (23). The multipliers are made left and right handed and assembled on each analyzer unit as shown (Fig. 2). Separate cables from each component connect them to the table frame.

f) Gear changing is accomplished by raising the index handle and setting the Lucite index finger on the proper ratio step as indicated by the pin and indicator plate engraving. Since the weight of the driving selsyn and index as well as some force exerted by the spring loading must be overcome by a counter force exerted on the index handle, this operation should be executed with care to avoid clashing of gears and abnormal wear of the Lucite finger. Experience shows that gear changing by this method is very satisfactory and one of the most simple of problem setup operations.

E - Adder

a) An adder is a component of the analyzer to which three electrical shafts may be connected in such a manner that the resultant rotation of one shaft is the algebraic sum of the other two. At the beginning of this section it was stated that the differential equation to be evaluated was separated into parts and transformed into integrals for solution. It is conceivable that a solution might consist of several of these parts which ultimately must be algebraically totalized in the machine to obtain the final solution. Proper connection of an adder into the interconnecting system supplies this requirement.

b) Each adder consists of a differential selsyn directly coupled to a motor/generator type selsyn by means of a flexible shaft coupling (Lord No. J-1211-1-5). One end of this coupling serves as a bearing surface for the damper spring assembled on the motor/generator selsyn shaft. Section 2-C discussed a differential selsyn with regard to its function. This function is again applied, differing mechanically only in that the differential selsyn shaft now drives another selsyn which in turn supplies an electrical shaft as an output. Thus, the differential selsyn provides two electrical shaft inputs; the algebraic sum of these shafts, electro-mechanically coupled to the rotor of the motor/generator selsyn, supplies an electrical shaft output which may in turn be utilized as stated above in Paragraph (a).

c) As mentioned previously, all differential selsyns used in the analyzer require a slip-ring and brush assembly. Differential selsyns with continuous shaft rotation were not obtainable, as a consequence, conversion of the Bendix No. C78249 type 5 was necessary. Mechanical details of the brush assembly are contained in UCRL drawings No. 3V 7111 and 3V 7101. Mention of these drawings is made here merely as reference to point out a few items of interest pertinent to maintenance or possible duplication of the analyzer.

d) Three flexible wires, connecting the rotor coils are fed through the rotor shaft to the motor terminal connections. A bakelite plug pressed into the end of the rotor shaft insulates the flexible wires and is cemented to them. Application of heat to the plug, from a soldering iron, loosens the cement and the plug may be removed without breaking the wires. The new slip ring mounting plug permits the flexible wires to be fed through it and insulated with varnished sleeving. This plug is then pressed into the bored end of the shaft, taking the space occupied originally by the bakelite plug. It will be found that the bored hole is not concentric with the axis of the rotor shaft, but wobble, due to eccentric mounting of the assembly on the plug, is corrected in the following manner. The slip ring assembly is fastened to the plug by means of a machine screw passing through an oversize clearance hole in the slip ring cap. After the wires are connected to the slip rings a copious amount of glyptal or insulating cement is applied to the plug and interior of the slip ring assembly. The assembly is wobbled on the machine screw into shaft alignment and finally the screw is set down snugly before the cement sets. Final wiring and phasing of the selsyns is simplified if the slip rings are wired and brushes attached so that the original internal wiring is retained at the motor terminal strip.

e) Brushes are made of 20 mil phosphor bronze wire bent in the shape of a hair pin, and are clamped, as shown in Fig. 11, under the terminal connector blocks. The inside brush is clamped under the number one terminal and the outside one to number three. A hole is bored in the center of the brush cover plate clearing the projecting end of the slip ring assembly so that the original cover plate may be used.

f) Two adders are assembled on a metal bar and wired to one electrical connector plug as a unit. Both units are bolted back to back and mounted vertically between the two horizontal members of the central T-section frame under the analyzer table.

F - Independent Variable Drive

a) Interconnection of a particular arrangement of the components to solve any differential equation requires that one of the shafts in the system be rotated by some external means; the independent variable (I.V.) is the shaft so driven. In order to provide an electrical shaft which may be connected to any selsyn of any element of the components, another selsyn must be used. This selsyn must be sufficiently large to supply exciting current to one or many selsyns connected to it. In other words, it must act as a low impedance source capable of supplying voltage to a load impedance which may or may not be equal to it, depending upon the requirements of the interconnecting system. Investigation into the many possibilities and requirements imposes a problem for which there is no elegant solution. In the event that a solution of an equation demands more power from the independent variable than its shaft can supply, obviously, that solution fails. This does not necessarily mean that an evaluation of the equation is impossible, but that rescaling of the coefficients or a different approach to the problem is indicated. Experience gained from use of the Illinois analyzer as applied to previous successful operations indicated that a Type 6 selsyn can be used as the independent variable unit.

b) Practical considerations necessitate several requirements of the I.V. drive system. Control of speed, as well as direction of rotation, are necessary to afford the operator means of setting up initial conditions on each component, and to provide drive control flexibility during the time a solution is being evaluated on the analyzer. For example, the speed must be variable to allow the operator to start the machine slowly under load, to run the machine slowly when following a steep input curve, and to establish the optimum analyzer speed consistent with desired accuracy. The direction of rotation must be reversible to allow the operator a means of reversing the drive to any shaft as required when setting the counters to initial conditions, or to reverse the drive during problem solution when found necessary to recheck previous data. Finally, a manual means of making fine rotational adjustments to the drive must be available.

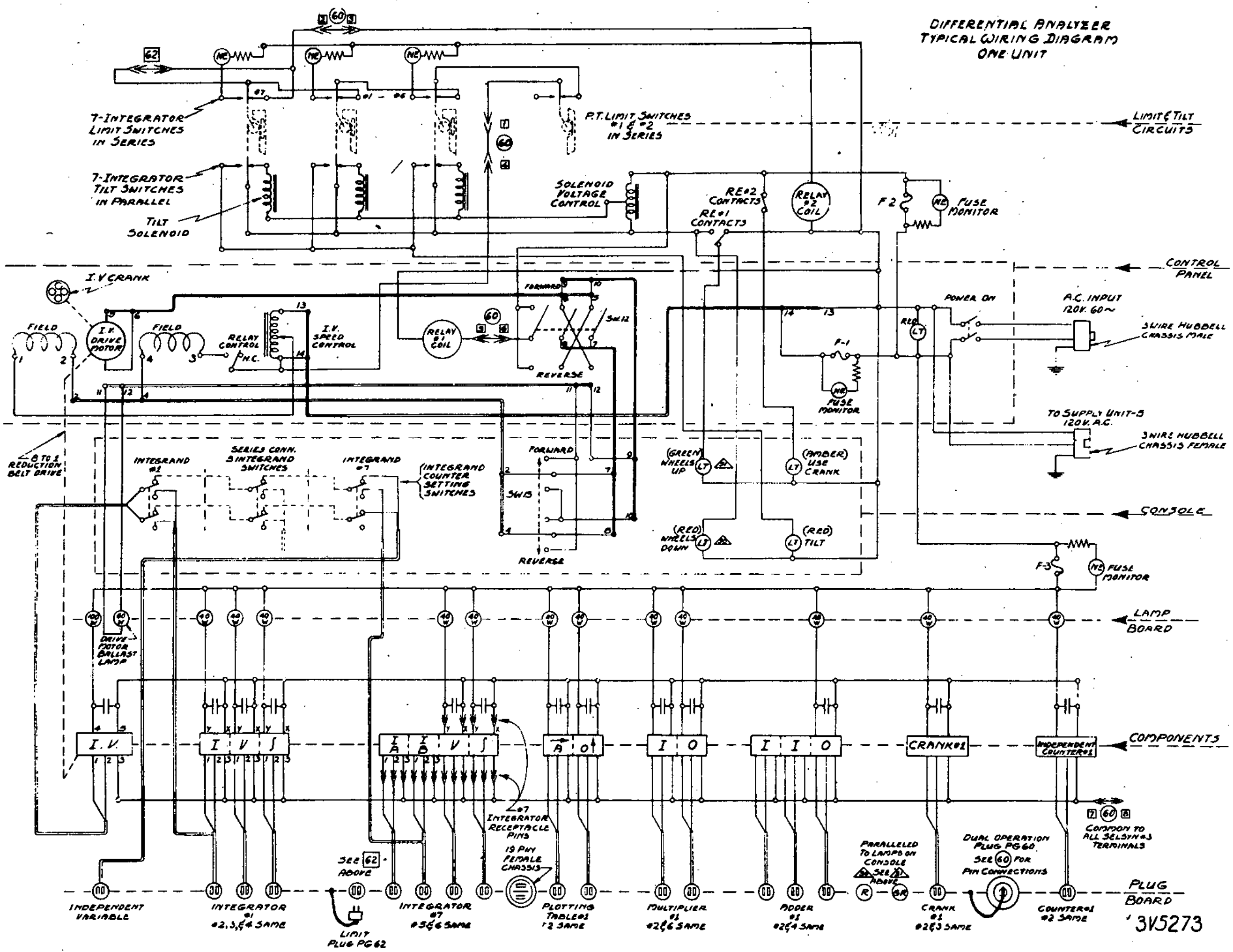
c) Essentially, the I.V. drive system consists of a Type 6 selsyn, mechanically coupled through an 8 to 1 belt and pulley reduction to a small reversible variable speed A.C. motor. On one end of the selsyn shaft is fastened a crank wheel accessible to the operator at the control panel. This wheel is in constant motion while the drive motor is operating, so is designed with no projections - finger holes and a knurled rim afford means of revolving it manually. Power is supplied to the drive motor through two electrically interlocked switches and a variable auto-transformer; the switches provide means of reversing the motor shaft rotation; the auto-transformer varies the speed of shaft rotation. One switch and the auto-transformer control are located on the control panel. This switch (SW 12, Fig. 15) is a three pole, three position toggle, with central position "off" or non-contacting. Two swingers of SW 12 are interlocked with the normally "off position" of SW 15 contacts. The third swinger connects control voltage to the "limit" and "tilt" circuits of the analyzer for either direction of the drive motor rotation. Switch 12 controls the actual starting and stopping operation of the analyzer when set up for problem solution. Switch 15 is a three position, three circuit, lever switch. The lever is spring-return actuated to a central position where its contacts provide the normal interlock circuit to Switch 12. Switch 15 is located on the vertical front panel of the console and is used in conjunction with the nine bat-handled toggle switches mounted on the console and wire-way to set initial readings of the counters.

d) The I.V. electrical shaft is connected to the plug board in series with the nine toggle switches, seven of which are indicated on Fig. 15. Contact positions of the switches as shown are spring-returned in this normal position. When a switch is operated, the I.V. electrical shaft is connected to drive that element of any component selected. For instance, if the switch designated "Integrand No. 1" is operated, the I.V. electrical shaft is momentarily disconnected from the plug board and connected to the integrand selsyn of integrator number one. Rotation of the I.V. shaft by means of the I.V. crank, or motor drive controls, causes the integrand selsyn shaft to turn as indicated by its integrand counter. The spring-return feature of these switches minimizes switch open-circuit errors and simplifies operation. Two similar switches not indicated on Fig. 15 are also connected in this series switch circuit of the I.V. electrical shaft. They are used to set the independent counters on a given reference reading prior to operation.

G - Console Indicator Lamps

a) All counter setting switches are mounted on the console or wireway in front of their associated components. Indicating lamps and the I.V. drive motor switch are mounted on the vertical console panel. Functions of the switches were discussed in Section 2-F. The indicator lamps will now be discussed in relation to operation of the electrical circuits indicated by them.

b) Two of the lamps located to the left of the I.V. drive motor switch are designated "WHEELS UP" and "WHEELS DOWN." Their jewels are green and red respectively. Indication of the lamps denote the position of the integral wheels of all integrators relative to whether they are in contact with the variable discs of the integrator or not. The green jewel indicates that the


DIFFERENTIAL ANALYZER
TYPICAL WIRING DIAGRAM
ONE UNIT
7-INTEGRATOR LIMIT SWITCHES IN SERIES
7-INTEGRATOR TILT SWITCHES IN PARALLEL
TILT SOLENOID
P.T. LIMIT SWITCHES #1 & #2 IN SERIES
LIMIT & TILT CIRCUITS
SOLENOID VOLTAGE CONTROL
RE#2 CONTACTS
RE#1 CONTACTS
RELAY #2 COIL
FUSE MONITOR
CONTROL PANEL
I.V. CRANK
FIELD
I.V. DRIVE MOTOR
RELAY CONTROL
I.V. SPEED CONTROL
RELAY #1 COIL
FORWARD
REVERSE
POWER ON
A.C. INPUT 120V. 60~
3 WIRE HUBBELL CHASSIS MALE
TO SUPPLY UNIT-3 120V. A.C.
3 WIRE HUBBELL CHASSIS FEMALE
8 TO 1 REDUCTION BELT DRIVE
INTEGRAND #1
SERIES CONN. 3 INTEGRAND SWITCHES
INTEGRAND #7
INTEGRAND COUNTER SETTING SWITCHES
(GREEN) WHEELS UP
(AMBER) USE CRANK
(RED) WHEELS DOWN
(RED) TILT
CONSOLE
LAMP BOARD
DRIVE MOTOR BALLAST LAMP
COMPONENTS
CRANK #1
INDEPENDENT COUNTER #1
INTEGRATOR RECEPTACLE PINS
19 PIN FEMALE CHASSIS
COMMON TO ALL SELSYNS TERMINALS
PARALLELED TO LAMPS ON CONSOLE
DUAL OPERATION PLUG PG60. SEE 60 FOR PIN CONNECTIONS
PLUG BOARD
INDEPENDENT VARIABLE
INTEGRATOR #1 #2,3,&4 SAME
LIMIT PLUG PG62
INTEGRATOR #7 #5&6 SAME
PLOTTING TABLE #1 #2 SAME
MULTIPLIER #1 #2&6 SAME
ADDER #1 #2&4 SAME
CRANK #1 #2&3 SAME
COUNTER #1 #2 SAME
3V5273

ZN223

Fig. 15

wheels are lifted when the control panel forward-reverse switch is in its central position. With the wheels lifted, set-up of the problem and patching of the interconnecting system may now be done safely since the input and output shafts of all integrators are disengaged. Set-up of the problem being completed, operation of the I.V. drive switch SW 12, connects power to the speed control, limit, and tilt circuits. This operates the tilt solenoids, lowering the integral wheels to their respective variable discs; the green lamp goes out and the red lamp indicates "WHEELS DOWN." Both lamps are duplicated at the plug board to warn against plugging into the interconnecting system while the wheels are down, resulting in damage to the components or invalidation of the initial conditions. The amber and red jewels at the right end of the console are warning indicators, indicative of the limit and tilt circuits respectively, and are designated "USE CRANK" and "TILT."

c) Note in Fig. 15 that all limit switches of the plotting tables and integrators can be connected in series, with the field winding of the I.V. drive motor through contacts of relay No. 1. When SW 12 on the control panel is operated, Relay No. 1 operates, completing this limit circuit. Relay No. 2 operates opening its normally closed contacts, which in turn "ready" the warning indicator lamp limit circuit. As mentioned before, if a normal operating displacement of any of these components is exceeded, one or more of the microswitches act to open the I.V. drive motor circuit, thus stopping the I.V. drive system.

d) For example, assume that limits have been exceeded on integrators number one and six, also on plotting table number one. The I.V. drive system has stopped, the "USE CRANK" lamp is indicating - all components have ceased to function. A quick inspection on the part of the operator, discloses that the warning neon lamp mounted above the integral wheel of integrator number one is indicating, also that the "USE CRANK" lamp is on. Further inspection might indicate the other two limits have been exceeded, but assume they go unnoticed by the operator. By operating "Integrand No. 1" switch and turning the I.V. crank in the proper direction to displace the variable disc within limits as indicated by the integrand counter reading, the neon lamp will go out on integrator number one. The I.V. drive is still not functioning, the "USE CRANK" lamp is still on, and the neon lamp located on integrator number six is now on. By using the same procedure as above, the neon lamp on integrator number six is extinguished, but the I.V. drive and "USE CRANK" lamp are as before. Inspection of the plotting tables show table number one "off limits." The beams are moved off limits by the operator as explained above (Sec. 2B, Par. d)), "USE CRANK" lamp is extinguished, and if the operator has not reduced the speed control on the I.V. drive motor to the off position, the I.V. drive will again take over in an attempt to operate the components.

e) Explanation of the procedure above may seem a complicated one to the reader, but in actual practice the operation may be achieved in a very short time interval. The following points may help to further clarify this operation. All limits exceeded during analyzer operation are indicated by the "USE CRANK" lamp. This lamp indication means that the I.V. motor drive is de-energized. It is then necessary to rotate the I.V. electrical shaft in order to displace component elements back to their normal operation position - the I.V. selsyn shaft must be rotated by means of the I.V. crank. In conjunction with the "USE CRANK" lamp, integrator limits are indicated by neon lamps, but only one at a time because of their series chain interlock. This method indicates the component first reaching a limit so that the operator's attention is directed upon it. Reaching successive limits on other integrators will cause these components to be indicated, but only one neon lamp is illuminated at a time, thus as one limit is corrected, its microswitch completes the circuit to the next component, causing its neon lamp to indicate, and so on until all integrator limit indicators have been "cleared." When all integrator limit indicators are cleared, the "USE CRANK" lamp will stay on only if the plotting table limits are exceeded. Thus, this lamp, if no neon lamps are on, indicates the limit of a plotting table has been exceeded, and determination of that table is made by inspection.

f) It should be further understood that all displacement limits are set to be the safe working limits when the analyzer is being driven automatically by the motor drive system. When these limits are exceeded, during automatic drive, the drive is momentarily disconnected, but if necessary, by means of the I.V. crank, the operator may continue the operation manually. Manual operation would be desirable if a maximum value of a function lay only a small amount beyond the limits set for automatic drive. In this case the operator may be able to "crank through the limit," allowing the automatic drive to again take over the operations.

g) In the event the actual surface of the disc is exceeded while the operator is attempting to "crank through the limit," the tilt mechanism is actuated, tilting the integral wheel as indicated by the "tilt" lamp. Refer to Section 3-A, Par. f) and i) for operation of the tilt mechanism. Displacing the variable disc by use of the I.V. crank and integrand switches, as discussed in this section, Par. d) and e), restores the interlock, removing indicating current from both the "tilt" and " USE CRANK" lamps.

h) The console indicator lamps thus serve two functions. Those on the left side of the console indicate the position of the integral wheels of all integrators when the main power is applied to the analyzer. Warning indicator lamps located on the right side of the console indicate that the automatic motor drive is disengaged and that further operation of the analyzer must be done manually while observing the action of the elements involved.

H - Console Independent Counters

Each of the independent counters mounted on the console employ small type-one motor selsyns. Each selsyn shaft drives a tenth-reading, 10,000 revolution count Veeder-Root counter through a pair of one to one right angle miter gears. Both counters are assembled in a manner which provides for slight adjustment of each gear train. A single cover fastened to the counter mounting plate serves to protect the gear trains. For purposes of setting to a reference, their electrical shafts can be switched to the I.V. electrical shaft in the same manner as the integrands of all integrators. These switches are located adjacent to the counters and properly designated. Their input electrical shafts terminate at the plug board. They require only a small amount of power, hence may be connected to any part of the interconnecting system and thus register the shaft rotation at that point. For example, it may be required to know the "count" of some shaft not directly connected to an integrand counter, or it may be necessary to set or obtain coordinate values of a point on a graph to better accuracy than can be obtained from the engraving on the plotting paper. In the latter case, a counter is connected to each selsyn driving the plotting table, and readings are taken from the counters at any given set of coordinate points. Abscissa or ordinate values read in this manner can be obtained to better than one-tenth of a unit of the graph paper, see Section 3-B, Par. i).

I - Lamp Board and Capacitors

a) Lamps mounted under the analyzer on the ends of each unit serve two purposes. First, they indicate electric current drain of the primary excitation winding of each motor/generator type selsyn. Second, they act as current limiters in the event a selsyn shaft is mechanically overloaded. Indication of current drain in each selsyn is necessary to provide the operator means of determining when components of the analyzer are patched, so that the phase of each selsyn involved is the same. Phase reference is established by minimum glow of the lamps. In operation the lamps barely glow; some may not glow at all depending upon the torque required of any one selsyn. Increased glow is indicative of increased loading and to some degree indicates selsyn shaft rotational lag. Under some conditions of analyzer operation loading can become excessive enough to cause pull-out of the slaved or driven selsyn as indicated by flashing of one or more of the lamps. Re-scaling of the component involved is then necessary to decrease its output shaft load.

b) Since criteria demands that normal analyzer operation be indicated by minimum glow of the lamps, proper choice of capacitor and lamp values must be made to obtain this. Single phase windings of all motor/generator selsyns are excited from the power source of 110v, 60 cycle A.C. In series with each winding is connected a suitable lamp, and in parallel with each winding, on the load side of the lamp, capacitors are connected. (See Wiring Diagram Fig. 15) Capacitor values are selected to resonate the inductance of each single phase winding when the output winding is driving a similar selsyn motor as a slave, thus the capacitors correct the power factor of the selsyns. The value to accomplish this is approximately 4, 8, and 12 microfarads for the type 1, 5, and 6 selsyns respectively.

c) The capacity of each lamp is selected so that when the proper amount of in phase current from the source supplies excitation voltage to the output electrical shaft of a slaved selsyn, minimum glow of the lamp is visible. Increased loading of the slaved shaft tends to displace the phase relation between the induced and exciting voltages of the system, causing more current to flow from the source. This increased current is then visible in the lamp and indicates to some extent the rotational lag in the electrical shaft coupling. Values of lamps in use are indicated on Fig. 15; differential-type selsyns require no lamps, the motor/generator type 5 selsyns employ standard frosted 40 watt, 120 v lamps - frosted to minimize visible normal operating glow.

d) The lamp board is arranged so that associated elements of components which the lamps indicate and protect are grouped together similarly to their control terminations on the plug board. All lamps are designated and shown on a chart using the symbolic notation for the components as shown on Fig. 15. This chart is conveniently located adjacent to the lamp board.

J - Plug Board

a) The components and supplementary accessories of the analyzer have been discussed, and reference has been made to an interconnecting system or suitable arrangement allowing a particular differential equation to be presented to the components of the analyzer. A unique feature of this machine as compared to other mechanical analyzers is the use of selsyns to drive the elements of all required components. All control wiring or electrical shafts of these components terminate at receptacles on a plug board. Interconnection of these receptacles by means of patch cords is then made possible, resulting in a very versatile system. Terminations of the control wiring for the various components and other receptacles on the plug board will now be discussed.

b) Note, with reference to Fig. 1, each plug board has mounted on it numerous two-conductor spade receptacles, framed by engraved bakelite strips. Engraving on these strips designates terminations of the components and their elements. Typical wiring of the components as shown in Fig. 15 indicates the method of connecting all selsyn No. 3 terminals to a common bus. This leaves two conductors on each selsyn which are wired to the two conductor receptacles. Polarizing these conductors is necessary to assure a systematic arrangement providing a means of introducing algebraic sign conventions.

c) The receptacles are mounted so when viewed from the front they appear as shown in Fig. 15. Counterclockwise rotation of the integrand selsyn as viewed from the shaft end was considered a rotation of positive sense, therefore all elements are polarized at the plug board to produce this sense of rotation. Conventions of plugging from one receptacle to another retain this sense of polarization by engaging the T-tap plugs in such a manner that the cable connecting the plug drops down from the body of the plug. Engaging a plug with its body rotated 180° thus assigns a negative sense to its opposite end. Rotational sense of all shafts are fixed according to these conventions at the plug board, but by means of "patch cords," the components may be interconnected to the system with due regard to algebraic sign.

d) Patch cords are made in two lengths. Each consists of two T-tap plugs connected together with a length of two conductor rubber covered flexible cable. Each patch cord is wired to retain the proper polarization. Red fiber insulating washers are inserted into the ends of the spade caps to distinguish the long from the short cords. Long cords are required to reach between the two plug boards when both units are connected for dual operation.

e) Fig. 1 shows the recessed receptacles engaged with blind plugs. These blind plugs provide circuit continuity when each table unit is operated as a separate analyzer and, therefore, must be engaged. When both units operate as a single large analyzer employing one I.V. drive system, these plugs are removed and connections are made between the tables to provide the same protection and control as a single unit operating alone. A suitable cable is provided for dual operation. This cable is fitted with mating plugs to fit the recessed 8-pin receptacles on each unit. One plug on the cable is painted red. When this cable connects both units for dual operation, the unit engaged to the red plug end of the cable is the controlling unit. Instructions for making this cable connection are engraved on each of the recessed receptacle escutcheon plates.

f) With reference to Fig. 15, the dual operation plug is designated as PG 60. Pin connections, showing the blind plug engaged, are indicated by numerals and a "circled 60." Points so indicated show the circuit continuity provided by the blind mating plug as engaged for single unit operation.

g) In dual operation these circuits are connected to both units in such a manner that the I.V. drive system of the unit controlling the operation is operated only by the controls on that unit. Also, the tilt, limit, and indicating circuits of both units are interlocked with this I.V. drive, permitting components of both units to be interconnected at their plug boards with protection afforded by these interlocked circuits.

h) Since the tilt circuit of both units is controlled by one unit only, during dual operation, the I.V. drive of the other unit can be used only for setting up initial conditions of its components and its time shaft cannot be used in the interconnecting system of both plug boards. Therefore, only one time shaft is available to drive both units as a single large analyzer in dual operation. Both consoles may be utilized as for single unit operation, but only the lamps on the console of the controlling unit give total overall indication, while those on the other unit indicate functions of that unit alone.

i) Immediately below the dual operation plug is a 120 volt A.C. three conductor receptacle. This receptacle is available to connect both units in tandem to the source of input voltage when they are used in dual operation for two reasons. First, it is desirable that both units operate from the same source of supply to assure that the voltage applied to both units is identical in amplitude and phase. Second, it is also desirable that only one power switch be required to control the supply to both units and be so arranged that either unit may be operated as the controlling unit.

j) The method of making this connection is best described as used in a typical set-up. For example, referring to Fig. 15, assume "Unit A" is connected in dual operation as the controlling unit. Its "A.C. input" 3 wire receptacle is connected by an appropriate cable to the source of power. Its "120 volt A.C." receptacle, mounted on the plug board, is connected by a similar cable to the "A.C. input" receptacle of "Unit B." The power switch, mounted on the control panel of "Unit B" is turned on; power is supplied to both units when the power switch on "Unit A" is operated. In the event the power switch on "Unit B" is not set to the "on" position, the relays in "Unit B" will chatter when the power switch of "Unit A" is operated. Relay chatter of this nature is in no way harmful to the analyzer, but the circuits should be restored as soon as possible to avoid undue wear of the relay contacts.

k) Functions of the various receptacles of the plug board have been discussed relative to operation of the components and as a means of interconnecting these components for dual or single unit operation. Two receptacles not previously discussed provide for operation of a spare integrator located remotely from each unit of the analyzer. These two receptacles are located below the "120 volt A.C." receptacle. One of these is a 2-wire receptacle engaged with a plug for normal operation; the other is a 19-pin receptacle to which the spare integrator may be connected. When a spare integrator is connected to one of the units, it is then designated as "Integrator No. 7." Removal of the 2-wire plug (PG 62 on Fig. 15) establishes the limit circuit for this integrator. PG 62 must be removed whenever the spare integrator is in use, otherwise no limit protection is provided for this integrator.

K - Spare Integrators

a) Two spare integrator components are supplied with the analyzer. Each is enclosed in a dust-tight metal box with a removable plexiglass cover. Metal handles on the box provide means for lifting and handling each unit, it is, however, recommended that the unit be handled as little as possible to avoid damage or misadjustment of the elements. Each may be used as a seventh integrator when connected to the plug board integrator receptacle of each unit, or may be used in any integrator position as a replacement in the event the original integrator fails or requires considerable repair.

b) When used as a seventh integrator it is connected by means of a cable to the appropriate receptacle on the plug board. Provision is made on the plug board for patching to its elements in the same manner as the six other integrators. Lamps are also provided on the lamp board to protect and indicate operation of these elements. These lamps must be unscrewed from their sockets to prevent false lamp indications when the spare integrator is not in use.

c) When used as a replacement integrator (i.e: replacing one mounted on the table unit), slight complications exist which must be fully understood before proper operation is obtained. As previously pointed out, there are four integrators, each employing three motor/generator selsyns to drive the mechanical elements. Each of these integrators requires three lamps on the lamp board and three receptacles on the plug board (Refer to Fig. 15). The remaining two integrators, Nos. 5 and 6, require two lamps and four receptacles due to the use of a differential selsyn drive on the integrand element of these components. The spare integrators are identical to those used in positions No. 5 and 6, and are, therefore, interchangeable without complicating normal operations.

d) When a spare is substituted for a component in the other four positions, the integrand lamp on the plug board is not required and must be unscrewed to avoid false indication. The "differential B" winding is terminated at the normal integral receptacle but due to the lack of a receptacle for the "integrand A" winding in these four positions, the "differential A" winding is terminated at the receptacle designated No. 7, differential A. For example, assume that the No. 4 integrator is replaced by a spare; the No. 4 integrand lamp is unscrewed from its socket, but not necessarily removed; differential B integrand, variable, and integral electrical shafts are available at the No. 4 "integrand," "variable" and "integral" receptacles respectively; the differential A integrand is available at the No. 7 differential A receptacle.

e) Plugs connecting each integrator to the frame of each unit are identical 19-pin connectors. The internal wiring of each integrator and the frame of each unit is so designed as to permit substitution of integrators with similar integrands but only the differential integrand type of integrator can be substituted in all positions if full capacity of the analyzer components is to be realized. Each integrator was adjusted with a definite unit and so designated, therefore, optimum results are obtained when used accordingly. For instance, table "unit A" was used in conjunction with one spare integrator which was "zeroed" and synchronized to operate with the other integrators of this unit. This integrator is designated as the "A" spare integrator and will operate best when used with the "unit A" table as the seventh integrator; however, it will operate satisfactorily in any replacement position.*

SECTION 4

ADJUSTMENTS AND TESTING

A - Integrators Setup for Adjustment

a) The previous two sections discussed the analyzer and its components, giving detailed description of its mechanical and electrical features. Most of the components have been discussed in such detail as to require no further specific elaboration, since the understanding of their operations is deemed

* See addendum A regarding space components.

sufficient. However, it is of major importance to understand that all motor shafts and the elements which are driven by them have maximum freedom consistent with minimum backlash or "lost motion." The success of proper analyzer operation is based upon minimizing the selsyn shaft load to avoid electrical shaft lag, therefore, all working parts must be adjusted to obtain this. This section will discuss the adjustments and methods of testing an integrator starting with the assumption that all the integrators are assembled mechanically and electrically on one of the analyzer units but none are adjusted for operation.

b) The integrator to be adjusted should first be removed from the analyzer table and located on a bench in view of the operators using the controls on the analyzer unit. Connection is made to the integrator by means of the spare integrator extension cable and the short cable originally used to connect the integrator to the analyzer unit. As a further aid, the elements of the integrator should be connected at the plug board as follows:

1) Patch integrator integrand to crank No. 1.

2) Patch integrator variable to crank No. 2.

c) Lamps corresponding to the two cranks and the three elements of the integrator position involved should be tight in their sockets. All other lamps should be loosened to open their circuits. When the main power switch is turned on, limit lamps on the console and integrators may indicate, causing confusion. To avoid this, since these adjustments will be made later, remove the 1.4 A. fuse, F-1, from its receptacle on the lamp board. Refer to Fig. 15. This disables the I.V. drive and limit circuit indicators requiring that all elements of the integrator under consideration be operated manually. Manual operation of cranks No. 1 and No. 2 will cause the disc to be rotated and displaced as required, thus simplifying movement of these elements.

B - Tilt Mechanism

a) Next, the tilt mechanism should be adjusted to allow the integral wheel to engage the surface of the disc when the I.V. drive switch (SW 12, Fig. 15) is operated. This is accomplished as follows:

1) With SW 12 in its central position, referring to Figs. 13 and 16, loosen the tilt bar clamp screw (17) to free the tilt arm (18).
2) Turn pivot set-screw (19) until integral wheel tire (33) just clears the variable disc.
3) With a small screwdriver hold pivot-screw (19) from turning and raise lifter arm (18) and bar (21) until solenoid plunger (23) is fully extended and stops against the double yoke casting (16).
4) Tighten clamp screw (17), lifter spring (20) should be almost relaxed but slightly in tension.

b) When SW 12 is operated, the lifter machanism should operate allowing the integral wheel to engage the disc. The full displacement of this mechanism raises the wheel about twelve thousandths of an inch; therefore, its adjustment is critical. Initial adjustments may be insufficient to obtain proper tilt displacement. If so, it is then necessary to raise the integral assembly by loosening the four screws (24) and relocating the double yoke (16). The best adjustment is obtained when the wheel clears the disc by about 5 mils in the raised position. These adjustments presuppose that the wear plate, or disc, is properly and securely clamped to the variable turntable. A warning is in order at this point. DO NOT ATTEMPT TO REMOVE THE VARIABLE TURNTABLE FROM ITS SHAFT MOUNTING, OR MAKE ADJUSTMENTS TO ITS MOUNTING SCREWS. Failure to observe this will entail considerable work to rectify the situation. See Section 3-A, Par. g).

C - Integral Wheel

a) To continue with the adjustments, assume that operation of SW 12

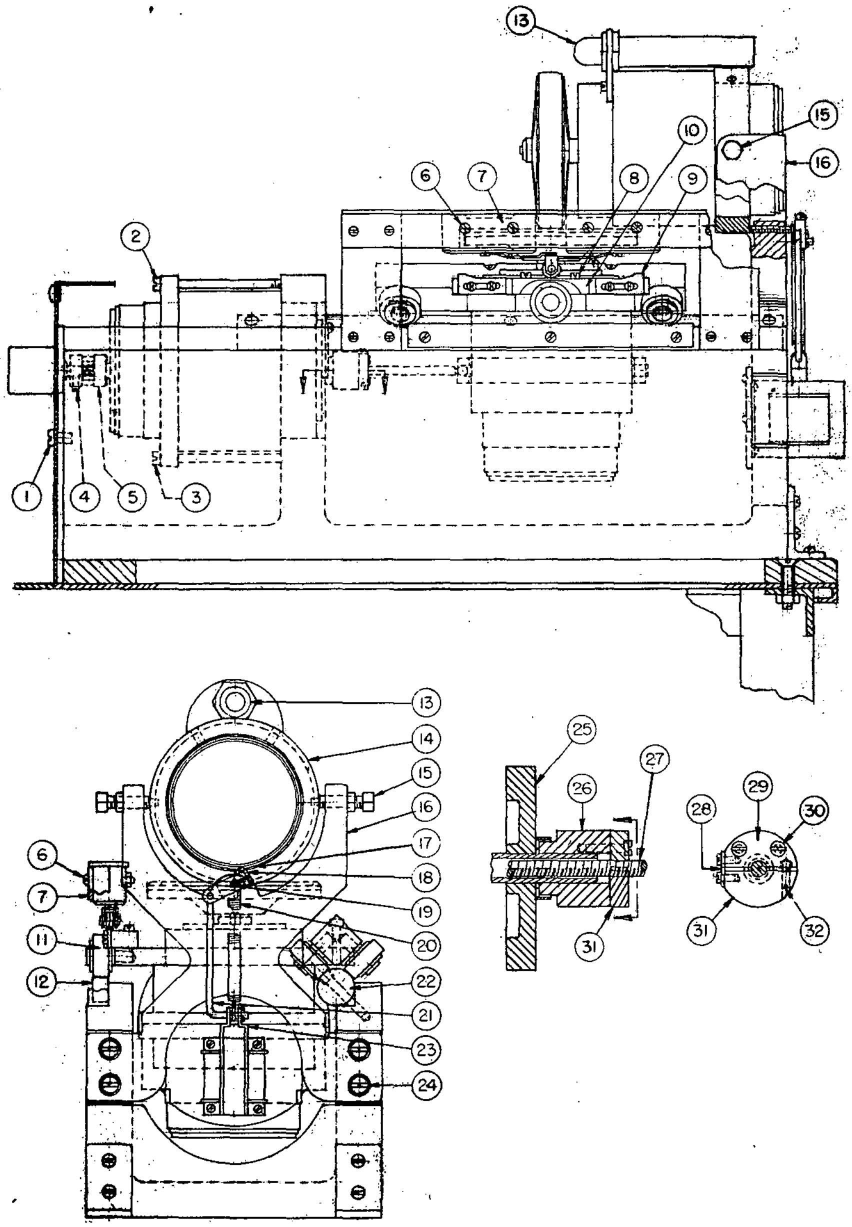

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Fig. 16

activates the lifter mechanism properly, the following adjustments are now made on the integral wheel assembly (Refer to Fig. 13)

1) With the wheel lifted, rotate it slowly by hand and sight between the wheel and disc; any slight eccentricity of the wheel will be visible as a variation of the separation of these elements. Remove screw (39) and spring (34).

2) Adjust the tension of the four screws (35) equally a fraction of a turn until the clearance is a minimum with no perceptible seizing. The ball joint should be smooth acting and very flexible.

3) Compare results as in 1) above; good adjustment is indicated by no visible eccentricity, however final adjustment should be made using a dial indicator in contact with the periphery of the wheel tire.

Final adjustments employing a dial indicator will indicate the eccentricity as well as the correctness of centering the wheel on the ball. Theoretically, the optimum adjustment is obtained when the centers of the ball (38) and the tire (33) are coincident in a point lying on the axis of the shaft of rotation. Absolute theoretical adjustment is not possible from a practical standpoint, but actual adjustment can be obtained resulting in very small errors of no consequence.

b) Preliminary alignment of the integral wheel axis of rotation with the major displacement of the variable disc axis is as follows:

1) Operate SW 12 to engage the wheel and disc.

2) Using both cranks (i.e., No. 1 and No. 2 as connected at the plug board) rotate the disc and displace it so that the wheel is operating a small distance from the disc center. Observe the

action of the wheel as it rotates. Wobble is indicative of unbalanced spring tension.

3) Relieve each quadrant of both springs (34) (Fig. 13) by bending them out; equalize the tension on opposing quadrants until the wheel wobble is reduced to a minimum. Slight wobble does not cause error but should be minimized to allow for maximum latitude of wheel tilt when changing direction of rotation.

4) Repeat step 2) but observe the action of the wheel as it passes through the center of the disc. The wheel should tilt slightly but erect itself and run true on both points either side of the disc center.

5) To obtain the condition in step 4), repeat steps 2) and 4), adjust the integral selsyn and wheel assembly into proper alignment by means of two pivot bolts (15) Fig. 16. Tightening one and loosening the other displaces the whole assembly horizontally.

Final adjustment is made when the integrand counters are set to reference zero. This is discussed in Section 4-F, Par. b).

D - Lead-Screw

a) Lead-screw alignment and adjustments are made as follows:

1) With the wheel raised from the disc, carefully crank the integrand shaft so that the lead-screw disappears into the integrand shaft. It may be necessary to reposition the lead-screw clamp ring. See Section 3-A, Par. n) and (42) Fig. 13.

2) Release the lead-screw clamp ring slightly and re-position it to allow for uniform threading action with no binding.

3) Tighten all set-screws beginning with set-screw (44) Fig. 13, at

the same time rotating the integrand lead-screw hub (26) Fig. 16 to avoid binding of the lead-screw.

4) At this point for a further check of setup (3), test for uniform contact friction between each of the four roller bearings and guide-way (22). Each bearing may be rotated slightly by hand for this test.

5) Crank the lead-screw out of the shaft assembly, observing the action of the lead-screw nut for any tendency to bind. Non-uniform threading action is noticeable as a reaction back through the electrical shaft coupling to the crank handle.

6) Increase or decrease the thread pressure of the lead-screw nut against the lead-screw by adjusting set-screw (32) until uniform threading action is obtained. Note, with reference to Fig. 16, this nut is made in two pieces. One-half (29) is fastened to the hub (26), the other half is spring loaded by means of spring (28) against the lead-screw. Set-screw (32) is threaded into the spring loaded half of the nut; therefore it can be adjusted to increase or decrease the contact pressure. A final adjustment can be made to assure proper pressure consistent with minimum backlash during reference zeroing. See Section 4-F, Par. c).

E - Integrand Counter Setting

a) Assuming the elements of all the integrators are properly adjusted to operate as detailed above, the next important adjustment of these components is that of setting their integrand counters. Many methods of accomplishing this are described in the literature and each have merit as applied to the mechanical construction of the analyzers described. Application of some of the methods previously used were tried and as results were not too gratifying, an attempt was made to devise a method whereby the analyzer could be used to solve the problem and adjustments made to retain these settings. No claim is made by the author regarding the basic principles involved, since ideas were taken from the literature and suggestions of interested persons. In any event the accumulation of these ideas evolved the present method which has proved most satisfactory.

b) From a practical viewpoint the three elements of the integrator have been referred to as ratio, input, and output electrical shafts. Since it is possible to set the ratio shaft to some given position such that the output shaft rotates at a constant ratio of the input shaft revolutions, it is also possible to use the integrator as a constant multiplier. For example, if the integrand lead-screw displaces the variable disc 40 turns from its true center, and the integration constant is actually 50; ($k = 1/50$ where $k' = 1/k$) 50 revolutions of the input shaft will cause the output shaft to rotate 40 revolutions or 0.8 of the input revolutions. A constant multiplier can be set to this same ratio as previously explained, and is therefore a standard of comparison producing an accuracy one would like to obtain from the integrators.

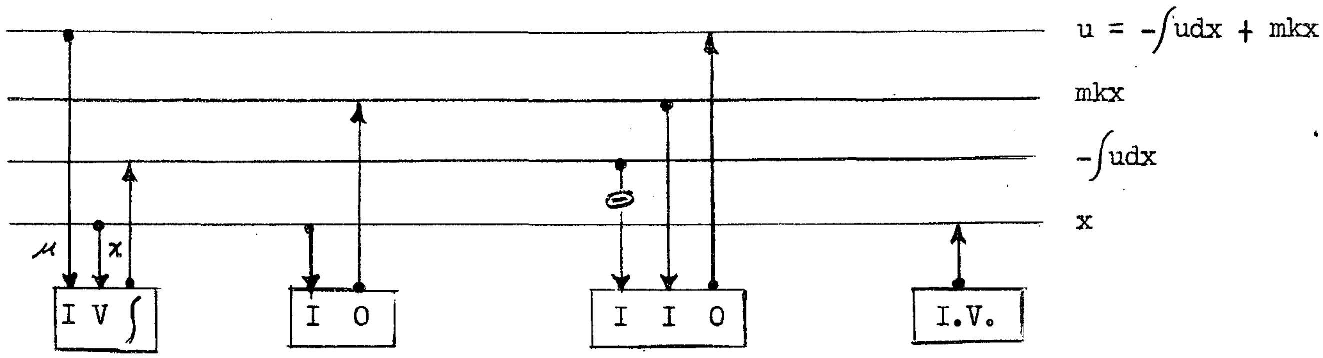
c) Now suppose the multiplier and integrator are driven by the same shaft with their outputs connected to an adder in such a manner that the difference of their shaft rotations is fed back to the integrator on its ratio shaft. This difference, corresponding to shaft revolutions, causes the integrand lead-screw to displace the variable disc until the output shaft revolutions of the integrator are equal to the output shaft revolutions of the multiplier. Therefore, if one sets the multiplier to any ratio m, and allows the I.V. drive system to operate these components until the integrator input to output ratio is constant, assuming for the moment that the integration constant is correct, then the product of this ratio and the integration constant (i.e., mk) represent the displacement of the lead-screw turns from true zero.

d) Figs. 17 and 18 show conventional wire diagrams of these connections. The differential equation being solved is equation (1). Two conditions are given for the same ratio indicating the method of obtaining positive and negative values of m. The four parallel bars are considered as shafts; arrows indicate the direction of drive and the elements of the components being driven. The negative sign on the wire diagram of Fig. 17 is conventional notation significant of a reversal of shaft rotation. Formal solution of the differential equation indicates the function being generated, which is one of many standard forms possible of automatic generation by the components. Theoretically, the true value for m as produced by the integrator can never be realized since this ratio is only possible for an infinite number of revolutions of the time shaft. However, for practical purposes the function converges so rapidly that the integrand counter reading of lead-screw displacement remains unchanged after 400 revolutions of the time shaft. Thus, employing this method, a means of setting the integrand counter is available.

e) To adjust integrator to reference zero:

1) Connect the components at the plug board per wire diagram of Fig. 17.
2) Operate the I.V. drive system until the integrand counter reading remains unchanged. (4 minutes at normal speed is sufficient.)
3) Record the integrand counter reading (assume the reading is 41.5).
4) Stop the I.V. drive, return SW 12 to its center position.
5) Change the wiring at the plug board as in Fig. 18 (one adder plug reversed).
6) Start the I.V. drive in the reverse direction and proceed as in

INTEGRAND COUNTER SETTING - POSITIVE READING



From Wire Diagram: $u = -\int u\,dx + mkx$

Differentiate $u' + u = mk$ (1)

The solution of the reduced equation, $u' + u = 0$, is

$$u = Ae^{-x} \tag{2}$$

Differentiate (2) to obtain u'

$$u' = A'e^{-x} - Ae^{-x} \tag{3}$$

Substitution (2) and (3) in (1)

$$A'e^{-x} = mk$$

$$A' = mke^{x} \tag{4}$$

Integrate (4)

$$A = mke^{x} + C \tag{5}$$

Where C is an arbitrary constant.

Now substitute (5) into (2), the general solution

$$u = mk + Ce^{-x}$$

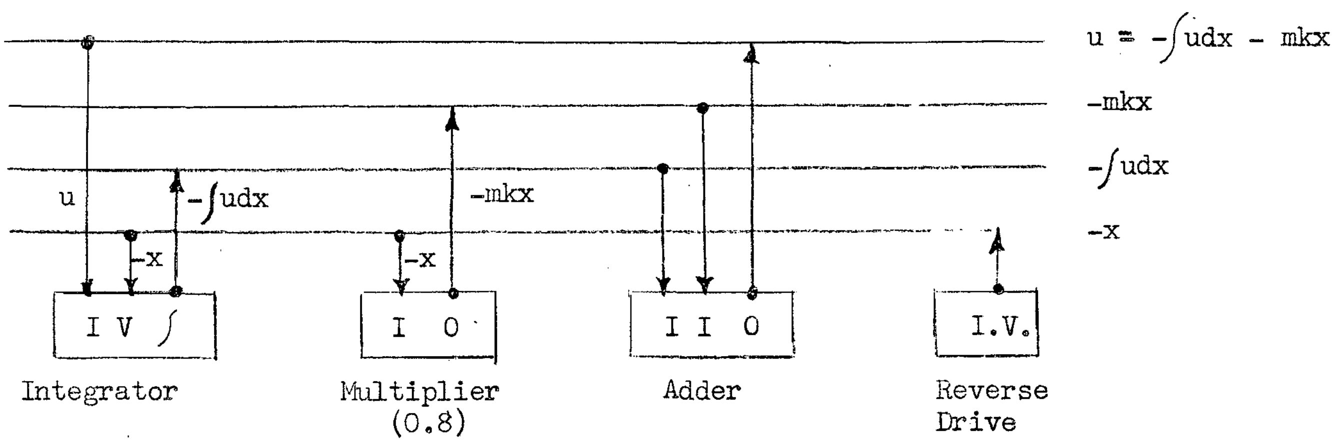
In the limit, as $x \to \infty$, $u \to mk$. $K = 1/50$ and $m = 40/50 = 0.8$

therefore $u = 40$.

The integrator is thus operating with an input to output shaft ratio of 0.8. This ratio represents 40 turns of the integrand lead-screw displacement from true zero.

Fig. 17

INTEGRAND COUNTER SETTING - NEGATIVE READING



From Wire Diagram: $u = -\int u\,dx - mkx$

Differentiate $u' + u = -mk$ (1)

The solution of the reduced equation, $u' + u = 0$, is

$$u = Ae^{-x} \tag{2}$$

Differentiate (2) to obtain u'

$$u' = A'e^{-x} - Ae^{-x} \tag{3}$$

Substituting (2) and (3) in (1)

$$A'e^{-x} = -mk$$

$$A' = -mke^{x} \tag{4}$$

Integrate (4) $A = -mke^{x} + C$ (5)

Where C is an arbitrary constant.

Now substitute (5) into (2), the general solution

$$u = -mk + Ce^{-x}$$

In the limit, as $x \to \infty$, $u \to -mk$. As before $k = 1/50$ and $m = 40/50 = 0.8$ therefore $u = -40$.

Integrator is operating with input to output ratio of 0.8, representing 40 turns of lead-screw displacement from true center of the variable disc or zero counter reading. Negative sign is significant of negative counter reading.

Fig. 18

steps 2) and 3). Assume reading is 61.5; this reading is considered negative or -(100 - 61.5) = -38.5).

7) The average of these readings, disregarding sign, is 40; with the integrator operating, set the counter to 60, stop the drive as in step 4), and repeat steps 1) through 7) until both negative and positive readings agree. One wants the counter to read zero for no rotation of the wheel when engaged at the center of the disc.

f) To set the counter (Refer to Fig. 16):

1) Engage the integrand counter shaft with the blade of a small screwdriver (access is gained through the small hole in the case of the counter) being careful not to turn this shaft, otherwise the setting will be upset.

2) With a 4-40 Allen wrench, loosen the coupling set-screw (4) slightly to free the counter shaft, at the same time restraining this half of the coupling from turning, using the wrench as a lever.

3) Set the counter to the true value as in step 7) above by turning the screwdriver blade. This adjustment requires considerable care to avoid moving the selsyn shaft.

4) Tighten set-screw (4) while restraining the counter shaft. Make sure that the coupling collar clears the body of the counter and the motion does not bind.

F - Final Adjustment of Elements

a) Paragraphs e) and f) above describe the method of obtaining the counter reference setting exemplified under optimum conditions. However, in some cases the readings of the counter may be erratic, and similar settings cannot be duplicated either side of zero. Assuming proper operation of the multiplier and adder in the combination of components used, there remain two final adjustments, either one of which will correct this, providing all adjustments of the integrator are correct up to this point.

b) First, referring to Section 4-C, Par. b), final adjustment of contact alignment of the wheel is made with the components connected as in Fig. 17, and operating at the limit condition (i.e., integrand counter reading 40). Carefully repeat the last part of step 5) Par. b), moving the pivot screws a small fraction of a turn at a time. Observe the counter reading while making this adjustment. Final adjustment is obtained when the counter reading is a minimum. The pivot bolt lock nuts should be secured, retaining this adjustment, and final test for zero should be made as outlined in Section 4-E.

c) The second adjustment is that of reducing the backlash in the integrand lead-screw assembly as cited in Section 4-D, Par. a) step 6). Repeat step 6) observing counter readings for several adjustments to the lead-screw nut during successive cycling to ratio limits. Optimum adjustment is obtained when the counter readings remain steady and are reproducible.

G - Integrator Limit Switch Adjustments

a) Section 3-G, Par. f) stated that definite displacement limits were set, establishing the range of automatic drive. This range is determined by the length of the lead-screw and diameter of the disc. The limits are set to use approximately 101 turns of lead-screw, which means each limit pawl is adjusted to operate a fraction of a turn beyond a reading of 50 on the integrand counters. Therefore, automatic operation is confined to a counter reading of 50 either side of reference zero. If the counter has been set to reference properly, readings of the counters may then be used to set the limit pawl.

b) To set the limit pawls (Refer to Fig. 16):

1) With the wheels lifted, use a crank to displace the variable disc until the counter reads 50 (positive or negative).

2) Adjust the pawl (9) against the microswitch roller until the switch operates the light (13).

3) Repeat steps 1) and 2) at the opposite end of the beam (10).

4) Adjust the rear microswitch on the bar (7) by means of the back two screws (6) so that a 1/32 in. vertical displacement of the roller operates the switch with the counter reading not greater than 50.3.

This adjustment should allow the I.V. drive to operate for counter readings of 50, either side of zero, but should stop the drive if these readings are exceeded by about a quarter turn of the lead-screw. Experience shows that under normal drive speeds these limits are sufficient protection, but for abnormally high speeds of drive the limits may be overrun due to the momentum of the driven elements; therefore, reasonable care should be taken to avoid this.

<u>H - Tilt Switch Adjustment</u> (Attention: analyzer operators)

a) Section 3-G, Par. g) et al., discussed the tilt mechanism and its function. It was also mentioned that the tilt microswitch operated after the normal displacement units were overrun to avoid damage to the wheel. Besides lifting the wheel to avoid dropping off the edge of the disc, this mechanism retains the wheel in a raised position until the disc is displaced back under the wheel. Adjustments to the microswitch operating this mechanism are outlined below:

b) To set the tilt microswitch (mounted nearest the integrand selsyn):

1) Loosen the front two screws (6) and position the microswitch so that its actuating spring is located as shown in Fig. 16.

2) Set the contact clearance between the spring and roller fork

of the limit switch to about 1/64 of an inch.

3) Displace the disc to operate the limit switch and observe the counter reading (not more than 50.3).

4) Continue to displace the disc one full turn of the lead-screw - the tilt mechanism should operate (not more than 51.5 on the counter). Reposition the switch 1/2 until proper operation results.

5) Repeat steps 3) and 4) at the other limit.

6) Repeat steps 3) and 4) and 5) until both counter readings are approximately equal.

c) It is not necessary for both counter readings to be equal as long as this adjustment allows for operation of the tilt mechanism within the stated limits. In order to avoid unnecessary complications, observe the following precautions:

1) Do not displace the disc so that the lead-screw is disengaged from its drive. <u>Maximum tilt limits as stated allow slightly more than two turns of the lead-screw to remain engaged.</u> Disengagement of the lead-screw voids the reference zero setting.

2) Do not change any adjustments to the pawls (9), the bar (10) or the limit microswitch mounting screws. Failure to observe this voids previous adjustments to the limit settings as described in Section 4-G.

I - Synchronizing Integrand Counters

a) All adjustments up to this point have been discussed in relation to one integrator. Consider now that two integrators have been adjusted properly, the first being connected in its permanent position on the analyzer and the second located remotely from the analyzer but still connected to it. Requirements imposed by conditions relative to the interconnection of components constrained to solve a given differential equation make it desirable that any integrand counter may be set accurately to zero during initial problem set-up. This requirement is especially necessary when two integrators have their integrand elements connected together, as may often be the case. Unfortunately, due to selsyn motor action, it is improbable that previous zero reference adjustments of any two will be such that the selsyn electrical shafts are also in phase at zero setting of the integrand counters. Therefore, it is necessary to synchronize all integrand counters. Integrators employing differential selsyns to drive the integrand element do not require this adjustment since they have two windings as previously discussed, one of which may be oriented by separate means to obtain the required conditions.

b) Considering the assumption of Par. a) suppose the first is integrator No. 1, and the second is integrator No. 2, and proceed as follows:

To synchronize the counters:

1) With power on, remove all previous patching from the plug board and set each counter to zero.

2) Patch both integrands together and by means of integral No. 1 switch and the I.V. crank set integrator No. 1 to zero. Integrator No. 2 must now be synchronized to read zero also.

3) Referring to Fig. 16 loosen screws (2) and (3) of integrator No. 2 just enough to permit rotation of the integrand selsyn in its mounting, but do not rotate it.

4) Hold the lead-screw hub (26) from turning and at the same time rotate the body of the selsyn until the readings of both counters are identical.

5) Tighten screws (2) and (3).

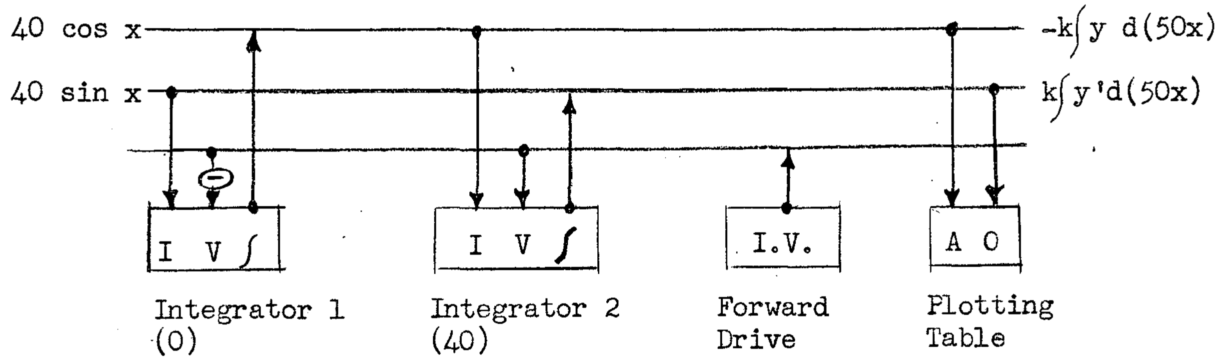
6) Finally, test synchronization by repeating step 2). If reasonable care is taken during these adjustments, both integrators are completely adjusted and the procedure outlined may be continued for the remaining units. However, before continuing to other units, a final check of zero reference should be made as outlined in Section 4-E Par. e).

J - Circle Test

a) Up to this point the assumption is that all components have been adjusted and tested individually. It is now necessary as a final test of their accuracy to check the operation of several of these units connected together. A method of checking two integrators at a time, as given in the literature, is that of the circle test. Faithful reproduction of a circle, as drawn autometically on the analyzer, requires that the constant of each integrator as well as the adjustments of all their elements be consistently identical and optimum. Comparison of integrators employing this method of testing provides a means of determining their proper operation and an index of their accuracy.

b) Fig. 19 shows the wire diagram and information for setting up the components to be tested. Equation (1) is the differential equation for a simple harmonic oscillator. For this test the general solution represented by equations (6) and (7) have the important property that $\cos^2 x$ plus $\sin^2 x = 1$ or simply $(y')^2$ plus $y^2 \doteq$ a constant. As the analyzer proceeds to solve the equation, four quadrants of a closed circle are drawn by the plotting table with a radius of 40 units if there are no mechanical or electrical backlash effects and the constants are very nearly equal. If these effects are present, the figure drawn will appear to be that of a spiral made up of arcs in each quadrant with increasing radii. If the figure closes but has a variable radius differing from the 40 units as set on the integrand counter, the integrator constants are not equal. Bad backlash effects are indicated by flattening of the figure

CIRCLE TEST



$$y'' + y = 0 \tag{1}$$

$$y' = -\int y dx \tag{2}$$

$$y = \int y' dx \tag{3}$$

For the analyzer:

$$y' = -\ k\int y d(50x) \tag{4}$$

$$y = k\int y' d(50x) \tag{5}$$

A particular solution of equation (1) is

$$y' = \cos x \tag{6}$$

$$y = \sin x \tag{7}$$

Substitute (6) and (7) in equations (4) and (5); noting that 40 sets the amplitude of oscillation and 50 turns of I.V. shaft to cancel k, (where $k = 1/50$)

$$40 \cos x = -\ 1/50 \int 40 \sin x\ d(50x)$$

$$40 \sin x = 1/50 \int 40 \cos x\ d(50x)$$

The analyzer solves, and plots

40 cos x against 40 sin x.

Integrand 1 counter set to 0
Integrand 2 counter set to 40

Plotting table abscissa set to 40 and ordinate set to 0,

Producing a circle of 40 units radius

Fig. 19

at each quadrant but under no circumstances were these visible on this analyzer. However, non-uniform flattening is indicative of binding in the plotting table or integrator lead-screws, or slippage of the integral wheels.

c) Backlash cannot be completely eliminated but it is possible to minimize these effects so the circle trace does close within the limits of observation and only slight increase of the counter readings is noticeable after several cycles. Mechanical backlash to a major degree can be corrected by adjusting the lead-screw nut pressure. Electrical backlash is proportional to loading and speed of the electrical shaft drive, therefore a low speed of drive and minimum loading is necessary to obtain optimum results. Drive speed should be just great enough to provide for smooth operation and thus overcome any tendency for the selsyns to oscillate. A writing rate of about 3 inches per minute employing the circuit of Fig. 19 has been found satisfactory, producing the numerical value for pi (π) on the independent counters within an error of 0.1 percent.

K - Determination of Integrator Constant

a) The integrator constant k' was introduced in Section 3-A, Par. b), where it was also stated that the maximum operating range of the integrator was said to have a gear ratio of one to one with respect to its input and output shafts. A method of obtaining an integrator ratio was also set forth in the discussion of "Integrand Counter Setting," Section 4-E, obtaining reading of 40 on the integrand counter for the case illustrated in Figs. 17 and 18, where $m = 0.8$. Since the design value of the integrator constant was intended to be 50 and it is possible to operate an integrator within this range, therefore, a method of obtaining the integrator constant by a direct reading of the counters is available for $m = 1$.

b) Referring to the wire diagrams of Figs. 17 and 18, it is necessary to disconnect the multiplier and re-connect the second adder input to the time shaft. This provides for direct drive and since m = 1, at the practical limit of drive, say 400 turns of the time shaft for each side of reference zero, an average of the counter readings, disregarding sign, is the value of the integrator constant. The average of several readings either side of zero, in the manner described determines the value of integrator constant to better than 1 part in 1,000 which is within the reading range of the counters.

SECTION 5

CONCLUSIONS

a) The analyzer described more than paid for its initial cost of construction in man hours saved during the first month of operation. Plans are being made for constructing a similar additional analyzer since demands upon the present unit have been so great. While the analyzer has been emminently successful in supplying information, as attested by its present operation, some additional components are contemplated.

b) Normally integrators are used to provide standard functions thus releasing the need for an operator and an input table, however, it sometimes is not only economic but necessary to extend the use of the analyzer by having several input tables available. Present usage has indicated that components of the analyzer should be increased to include two additional output tables thus permitting the present four tables to be used as input tables when desired. Thus it can be seen that regardless of the reasoning behind any one design, provision must be made for extending the usefulness of the analyzer by additional accessories, within reasonable limits. The limiting factor in this case is dictated by the maximum torque supplied by the I.V. drive system which in turn is dependent upon the number and arrangement of components required to solve a given problem.

c) Existing disadvantages of the present analyzer which could be improved are: (1) removal of the existing electrical patching hazard and, (2) re-design of the adders.

d) The first is significant from the standpoint of personnel protection. Since all patching is done by means of plugs with exposed terminals when one plug is engaged to the plug board the other end of the patch cord is not protected and, therefore, constitutes an electrical hazard. Due to the necessity of having to design and make a suitable plug involving a further expenditure of time, and since the operating personnel had prior experience with this system as employed on the Illinois analyzer, this disadvantage was considered secondary. It can be rectified at a later date. Retractable protective sleeves can be designed and attached to the present T-taps eliminating the present hazard for an approximate cost of $500.

e) Redesign of the adder component to replace the differential selsyn by either a larger unit or a mechanical differential gear mechanism should be given consideration. Either substitution would provide a means for obtaining greater shaft stiffness and improve the components, but it would also involve further research and design. Replacing the present adder with larger differential selsyns is the more economical of the two alternatives and should be investigated first, but for either substitution the approximate cost should be about $1,500 for the complete conversion. Present design of the adder followed the design of adders used in the Illinois analyzer which at that time were considered entirely satisfactory, but as construction and research proceeded, it became evident that improvements of this unit were necessary. Because of this the location of adders was so chosen as to permit future conversion without involving great physical change to the present analyzer.

f) In regard to maintenance of the analyzer, relatively little is known regarding actual operating time before failure of its working parts or decreased accuracy due to wear. Every attempt was made in the design to allow for adjustment or replacement of all working parts as well as protection of all working surfaces from dust or oxidation. A routine cleaning and inspection of the integrators is suggested on a bi-monthly basis, depending upon usage and atmospheric conditions. A very thin film of oil is all that is normally required to prevent oxidation of the integrator elements. It is imperative that all finger prints or oxidizing deposits are removed after adjustment of these elements before normal operation is begun. The design is rugged to allow for precise and stable adjustment, and under reasonable operation should not require a complete inspection more often than twice yearly. Attached to this report is a complete list of parts and reference wiring diagrams intended as an aid to maintenance men or persons interested in constructing a similar differential analyzer.

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Information Division
3/18/52 bm

COMPLETE DRAWING LIST FOR DIFFERENTIAL ANALYZER

Drwg. No.	Quan.	Title
	REFERENCE	
3V 5164	-	Tie Point Wiring Schematic
5174	-	Selsyn Capacitor Wiring
5183	-	Plug Board Wiring
5193	-	Selsyn Lamp Board Wiring
5203	-	Console Wiring Schematic
5212	-	Console Plug Wiring
5223	-	Crank and Drive Selsyn Wiring
5231	-	Plotting Table Wiring
5242	-	Wiring Tables No. 1 Block
5252	-	Wiring Tables No. 2 Block
5273	- Fig.15	Typical Wiring Diagram 1 Unit
7201	-	Drawing List (this)
7331	-	Electrical Parts List
7341	- Fig.17	Integrand Counter Setting-Positive Reading
7351	- Fig.18	Integrand Counter Setting-Negative Reading
7361	- Fig.19	Circle Test
	PICTORAL	
3V 7211	-	Complete Analyzer Fig. 1
7221	-	One Unit Front View Fig. 2
7231	-	Multiplier Fig. 3
7241	-	Table-Exploded View Fig. 4,5,6
7251	-	Plug Board Wiring (Internal) Fig. 7
7261	-	Lamp Board Wiring (Internal) Fig. 8
7271	-	Integrator-Simple Pictoral Fig. 9
7281	-	Integrator-Rear, Front & Side View Fig. 10,11,12
7291	-	Integrator-Side & End Detail Fig. 13
7301	-	Integrator-Disc & Wheel Detail Fig. 16
7313	-	Multiplier Assembly Fig. 14
	INTEGRATOR	
3V 5871	14	Integrand Support Ring
5881	14	Integrand Lead Screw
5891	14	Integrand Lead Screw Clamp Ring
5901	14	Integrand Lead Screw Nut
5911	14	Integrand Lead Screw Clamp Button
5921	14	Integrand Lead Screw Nut Mount
5932	As Req.	Integrand Counter Bushing and Shaft
5941	-	Integrand Counter Coupling Assembly
5951	14	Integrand Counter Mounting Plate
5961	As Req.	Integrand Spacer Ring

COMPLETE DRAWING LIST FOR DIFFERENTIAL ANALYZER

Drwg. No.	Quan.	Title
	INTEGRATOR	
3V 5971	70	Variable Bearing Support Pins
5981	14	Variable Wear Plate
5991	42	Variable Wear Plate Lugs
6001	14	Variable Turntable
6011	14	Variable Bearing Beam
6021	14	Variable Mounting Plate
6031	14	Variable Guide Way
6041	14	Variable Bearing Way
6052	14	Variable Adjustable Limit Beam
6062	28	Variable Adjustable Limit Pawl
6072	28	Variable Integrator Limit Mounting Post
6082	14	Variable Integrator Limit Sw. Mount Bar
6092	14	Variable Integrator Limit Sw. Cover
6101	14	Integral Lamp Bracket
6111	14	Integral Tilt Rod
6121	14	Integral Tilt Arm
6131	14	Integral Support Clamp
6143	14	Integral Mounting Casting
6151	28	Integral Pivot Bolt
6162	14	Integral Solenoid Mounting Plate
6171	14 ea.	Integral Wheel Spacer and Cap
6182	28	Integral Wheel Disc
6191	14	Integral Wheel Stud
6201	28	Integral Wheel Spring
6212	14	Integral Wheel Tire
6224	14	Integrator Base Casting
6234	2	Integrator Single Dust Cover Base
6243	2	Integrator Single Dust Cover Top
6252	2 ea.	Integrator Single Dust Cover Base Handle
6261	28	Integrator Base Angle Mounting Bracket
	MULTIPLIER	
3V 7313	-	Multiplier Assembly
6271	12 ea.	Multiplier Gears
6281	12	Multiplier Eight Tooth Gear
6291	12	Multiplier Sixteen Tooth Gear
6301	12	Multiplier Hanger Bracket
6311	12	Multiplier Base Plate
6321	12	Multiplier Gear Cluster Bushing
6331	12	Multiplier Gear Bushing
6341	12	Multiplier Gear Collar
6351	12	Multiplier Front Plate
6361	12	Multiplier Index
6372	12	Multiplier Index Arm

COMPLETE DRAWING LIST FOR DIFFERENTIAL ANALYZER

Drwg. No.	Quan.	Title
	MULTIPLIER	
3V 6382	12	Multiplier Index Finger
6391	12	Multiplier Index Indicator
6401	12	Multiplier Shaft
6411	12	Multiplier Spring
6423	2	Multiplier Guard
6432	12	Multiplier Index Handle
	PLOTTING TABLE	
3V 6443	4	Plotting Table Base
6451	8	Plotting Table Clutch Wheel
6461	8	Plotting Table Clutch Spring
6471	8	Plotting Table Mating Clutch Wheel
6481	8	Plotting Table Lead Screw
6492	2 ea.	Plotting Table Ordinate Drive Block
6502	2 ea.	Plotting Table Abscissa Drive Block
6511	4	Plotting Table Drive Block Arm
6522	8	Plotting Table Beam Release Button
6532	4	Plotting Table Square Beam Outrider
6542	2	Plotting Table Carriage-Left Hand
6552	2	Plotting Table Carriage-Right Hand
6561	8	Plotting Table Beam Button
6572	8	Plotting Table Motor Mount
6582	8	Plotting Table Motor Mount Plate
6591	4	Plotting Table Abscissa Outrider Block
6601	8	Plotting Table Index Cup
6611	12	Plotting Table Pen Holder
6621	4	Plotting Table Lead-Screw Guard
6631	8	Plotting Table Limit Detent Bar
6642	4 ea.	Plotting Table Limit Linkage Bar
6651	16	Plotting Table Limit Reset Spring
6663	-	Plotting Table Limit Assembly
6673	4 ea.	Plotting Table Ways
6681	4	Plotting Table Lead-Screw Guard (Absc.)
	ADDER	
3V 6692	2	Adder Mounting Plate
6702	2	Adder Plug Bracket

COMPLETE DRAWING LIST FOR DIFFERENTIAL ANALYZER

Drwg. No.	Quan.	Title
3V 6714	2	Table Top
6723	see dwg.	Ends, Back, and Lamp Cover Panel
6733	1 ea.	Plug Board Back Panel
6743	1 ea.	Right and Left Hand Lamp Mounting Plate
6754	2	Frame
6913	1 ea.	Lamp Mounting Shell and Addendum
7322	-	Lamp Mounting Detail
6924	2	Control Panel
6934	-	Plug Patch Panel Dimensions (Fabs)
6944	see dwg.	Plug Patch Panel Designation Detail
6954	2	Wiring Tray
6964	2	Front Wiring Tray
6974	2 ea.	Console and Wire Way Assembly
6984	-	Console and Plate Dimensions
6994	-	Console Plate Dimensions Addendum
7004	2	Integrator Dust Cover Base
7014	2	Integrator Dust Cover Top
7024	2 ea.	Table Plug Cover
7031	12	Table Plug Cover Mounting Angle
7043	4	Adjustable Caster Bracket and Assembly
7051	4	Swivel Caster Modification
7063	-	Caster Mounting Dimensions
7072	2	Independent Counter Cover
7081	2	Independent Counter Mounting Plate
7091	28	Selsyn Clamp Braket
7101	6	Slip Ring Mounting Plug
7111	6	Slip Ring Assembly
7121	62	Oscillation Damper
7131	62	Oscillation Damper Spring
7141	24	Wire Barrier Post
7152	6 ea.	Crank Collet and Nut
7162	6	Crank Plate
7171	6 ea.	Crank Knob and Pin
7183	-	Crank Assembly
7192	2	Independent Variable Draive Crank Wheel