United States Patent

Clark, Jr.

[15] **3,653,161**

[45] **Apr. 4, 1972**

[54] METHOD AND APPARATUS FOR TURNING WORKPIECES AND UTILIZING PROGRAMMED DATA

[72] Inventor: **Stephen C. Clark, Jr.**, Phoenixville, Pa.

[73] Assignee: **The Ingersoll Milling Machine Company**, Rockford, Ill.

[22] Filed: **Jan. 25, 1971**

[21] Appl. No.: **109,522**

Related U.S. Application Data

[62] Division of Ser. No. 790,323, Jan. 10, 1969.

[52] **U.S. Cl.** ..... **51/165 TP**, 51/49, 51/289 R, 318/569

[51] **Int. Cl.** **B24b 5/04**

[58] **Field of Search** ..... 51/49, 165 R, 165 TP, 165.71, 51/165.74, 165.75, 165.76, 165.77, 289 R, 326, 327; 82/14 B, 14 D, 21 B; 318/569, 570, 571

[56] **References Cited**

UNITED STATES PATENTS

3,007,096	10/1961	Tripp	318/571
3,056,240	10/1962	Morgan et al.	51/165 R
3,088,250	5/1963	Hold et al.	51/49 X
3,391,497	7/1968	Parrella et al.	51/49 X
3,422,583	1/1969	Stuckey et al.	51/289 R

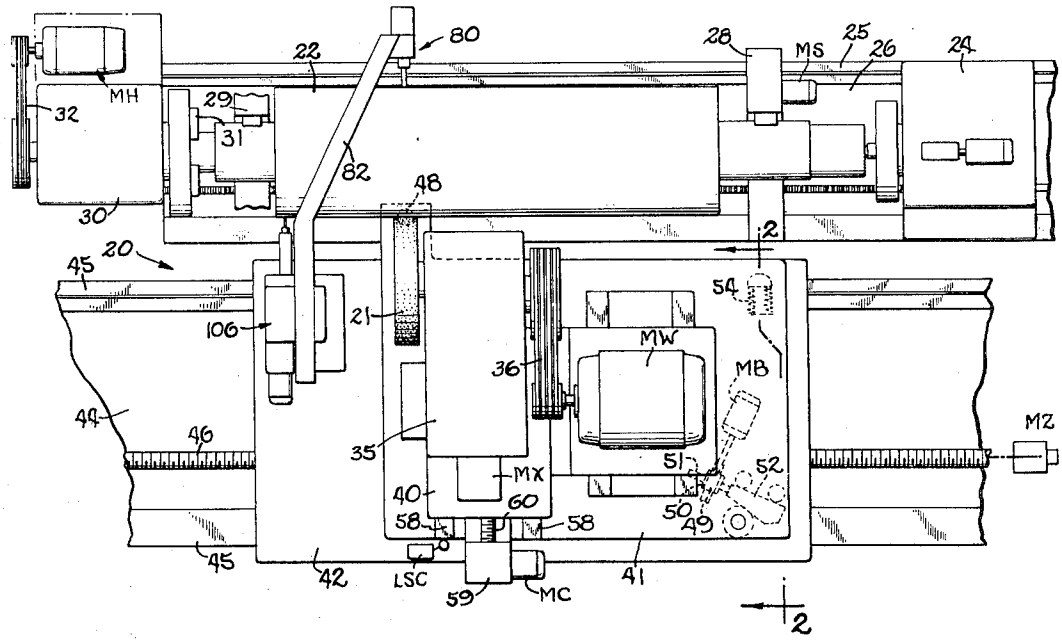
Primary Examiner—Lester M. Swingle

Attorney—Wolfe, Hubbard, Leydig, Voit & Osann, Ltd.

[57] **ABSTRACT**

Disclosed here are methods and automatic apparatus for grinding cylindrical workpieces, such as the contoured rolls used in metal rolling mills. The methods and apparatus involve (1) automatic finding of the lengthwise center of rolls of different and undetermined lengths so as to establish a reference position for the execution of a numerically programmed path defined relative to the center of a roll as a point of symmetry, (2) the storage of the successive instructions of multi-axis movements making up a numerically defined profile or contoured path, and the use of those instructions repeatedly and in whole or in part as called for by different ones of a sequence of commands read from storage and executed in succession, (3) the automatic alignment of the roll axis parallel to the longitudinal axis of motion in a grinding machine by pivoting of one end of the roll about the other until the sensed difference in positions of the roll surface, along an axis transverse to the longitudinal axis and at locations near opposite ends of the roll, is changed to a predetermined fraction of the originally sensed difference, (4) the initiation of grinding passes from that end of a roll which is largest in diameter, so as to avoid "-digging in" or increasing the depth of wheel bite as the wheel moves lengthwise of the roll, (5) the execution of continuous passes of the grinding wheel with pre-programmed values of feed rate, wheel speed, roll speed, continuous infeed and incremental infeed until a pre-programmed thickness of material has been removed from the roll surface, and (6) the grinding down of a roll until it is reduced to a diameter equal that of a previously ground roll of a matched pair. These functions are all obtained by the calling out and execution of pre-established routines in response to the reading from storage of pre-programmed sequence commands, so that in the disclosed method and apparatus there is an automatic progression from each type of operation to the next, and with the following of numerically defined profile whenever it is required.

11 Claims, 27 Drawing Figures



PATENTED APR 4 1972

3,653,161

SHEET 01 OF 18

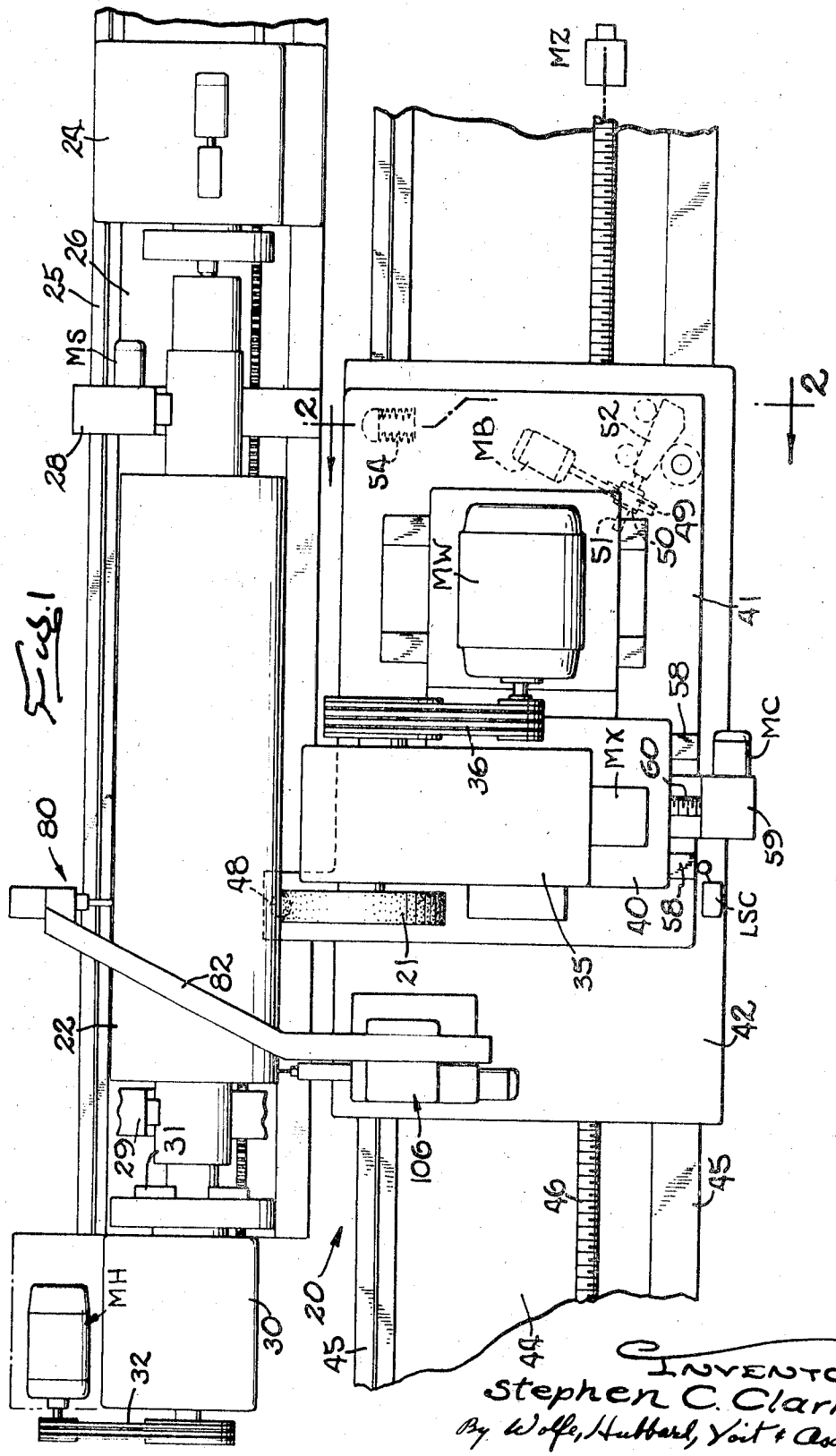


Fig. 1

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

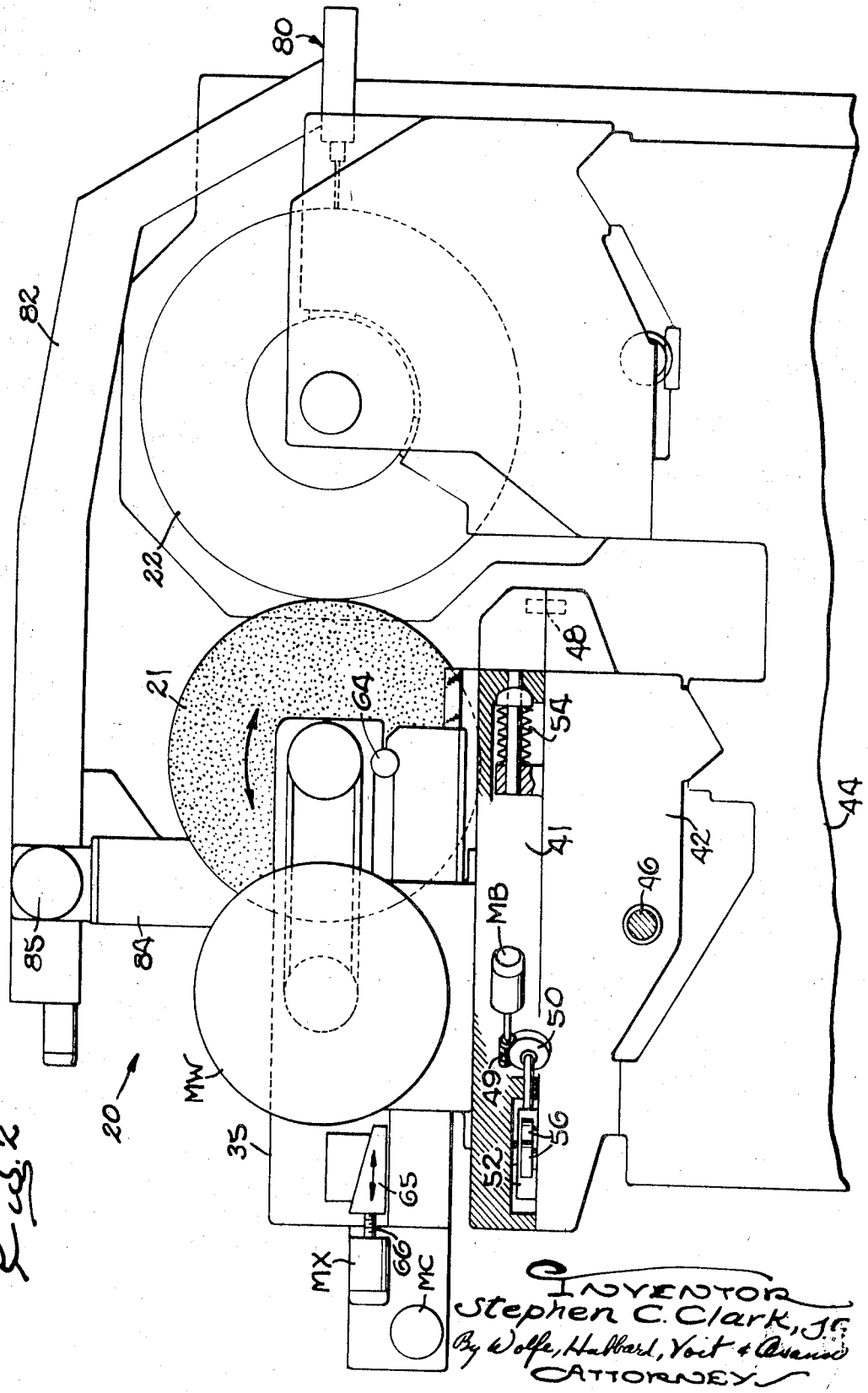


Fig. 2

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

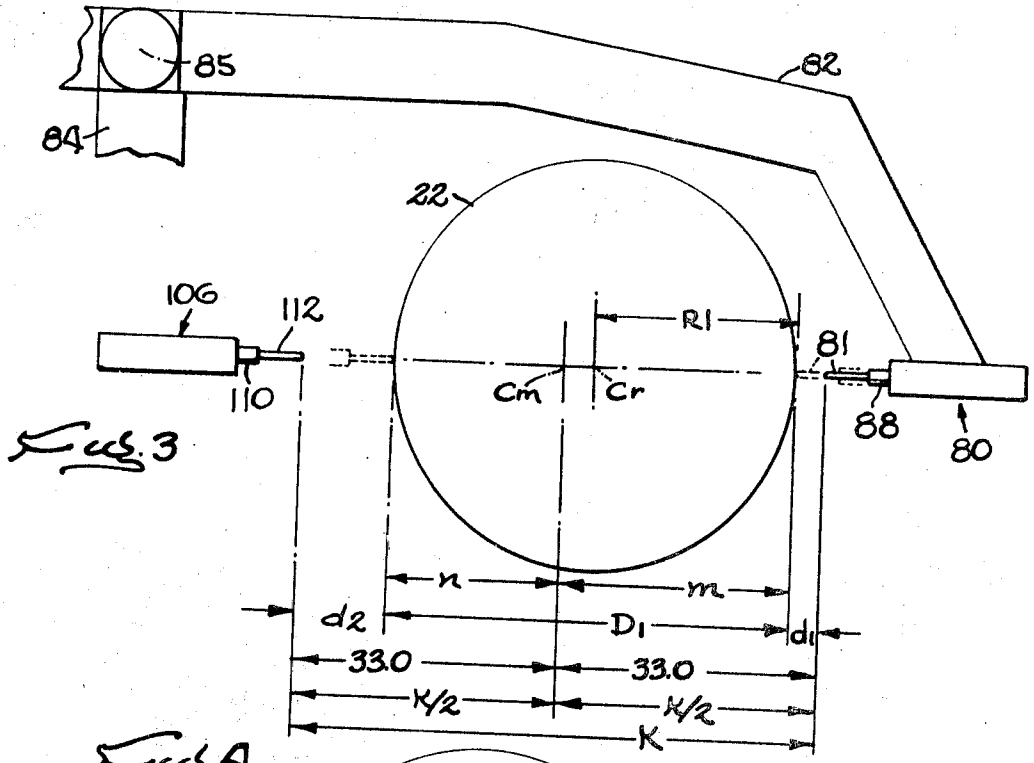
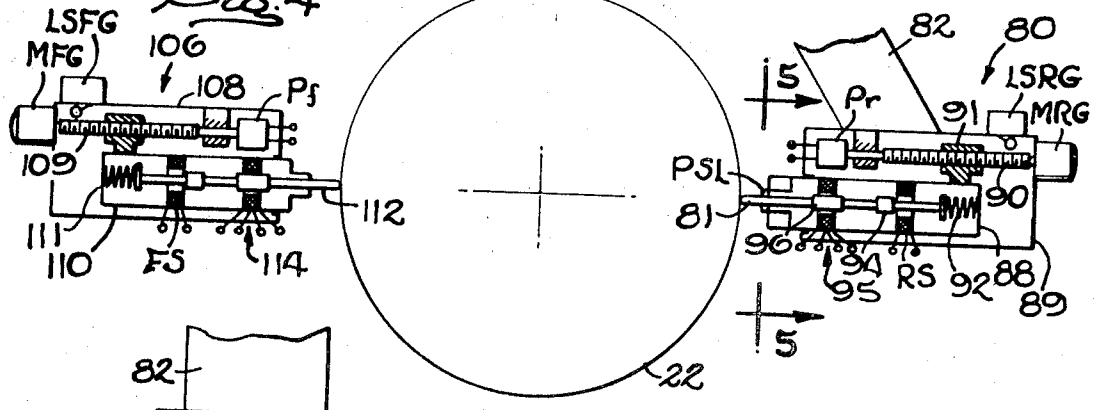


Fig. 3

Fig. 4



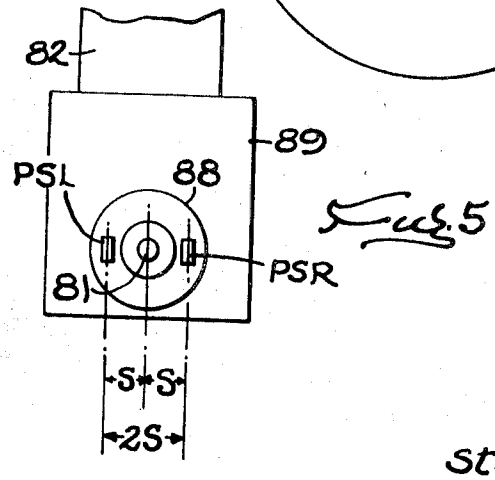


Fig. 5

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

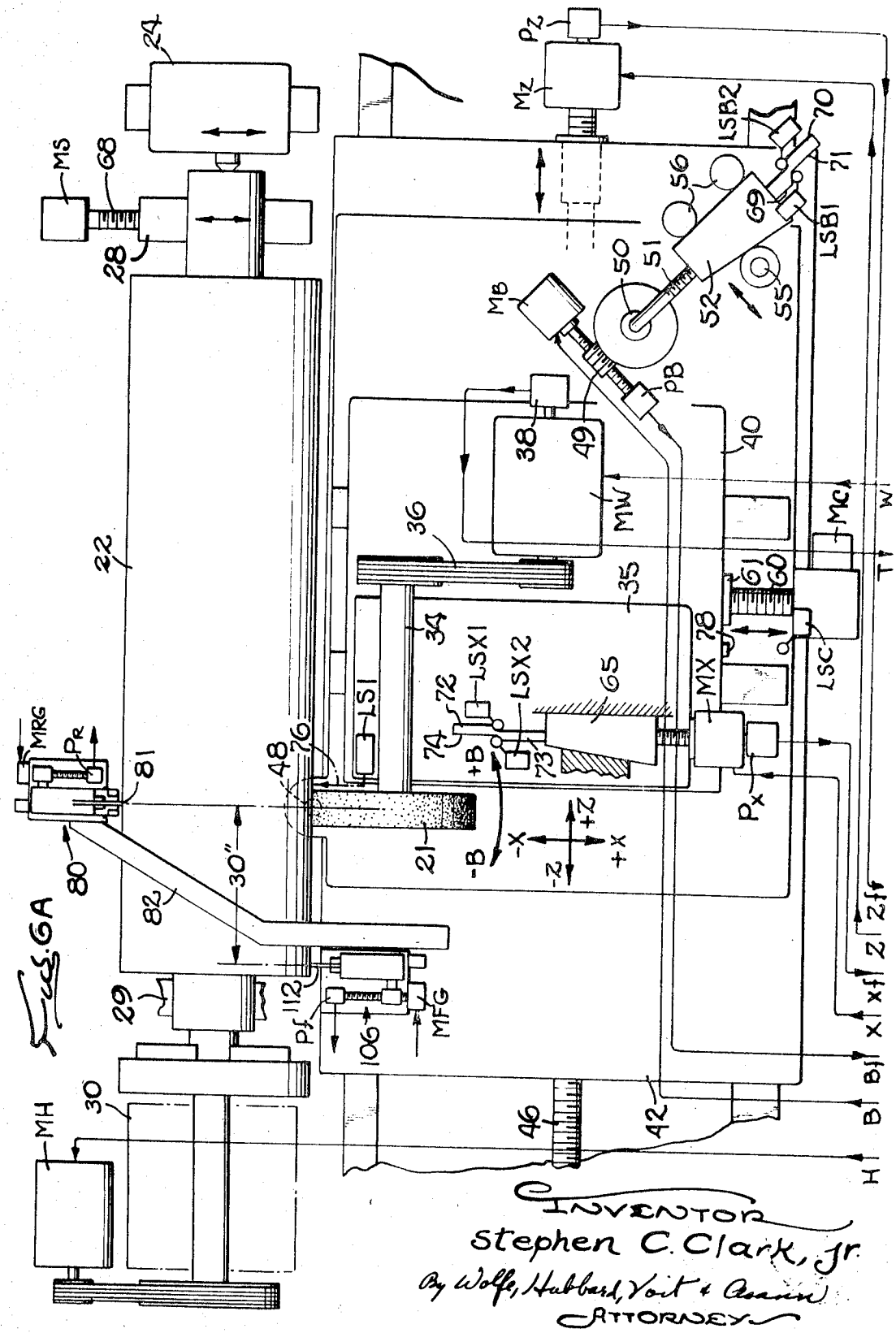
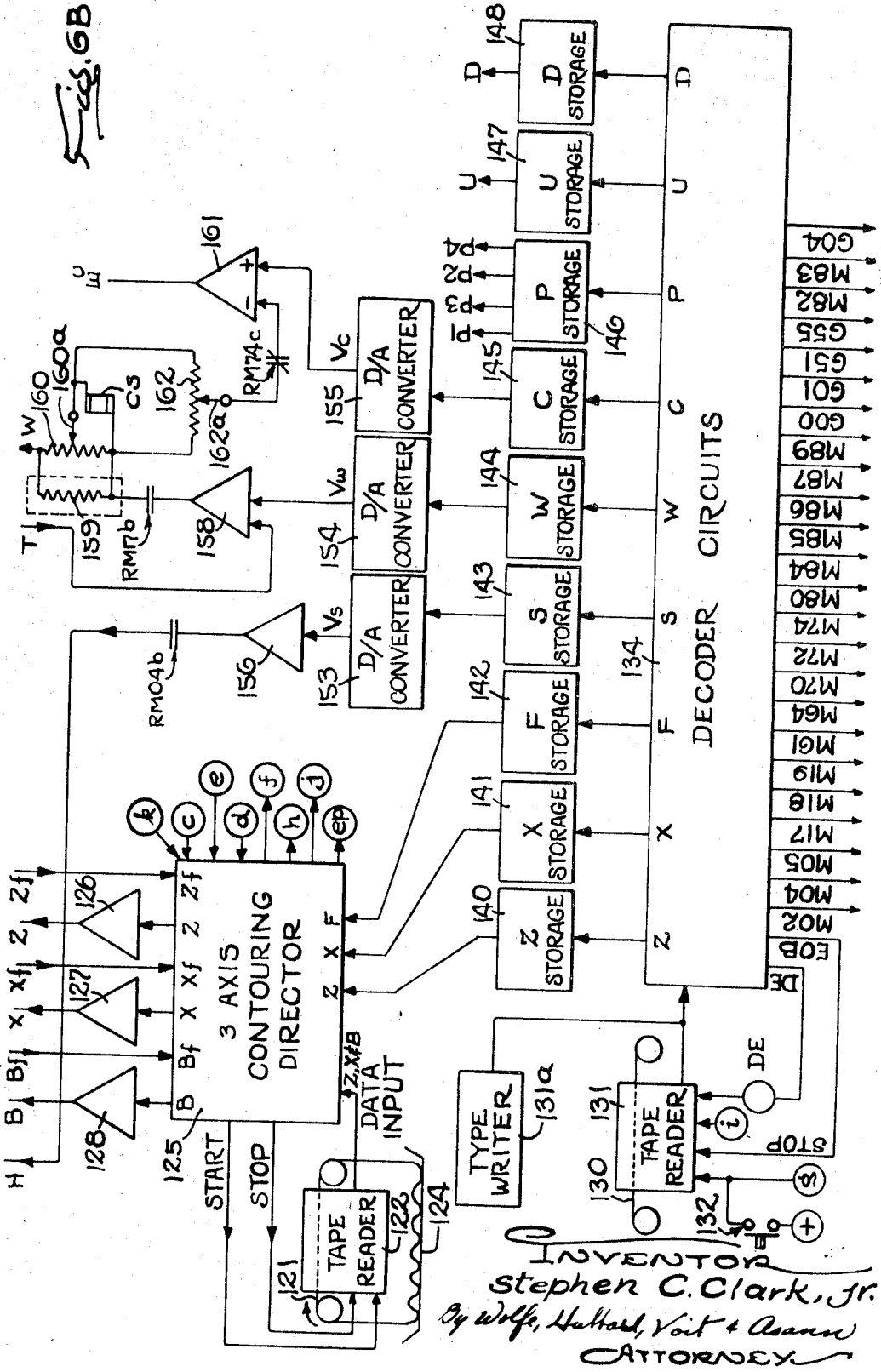


FIG. 6A

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

Fig. 6B



INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

Fig. 7

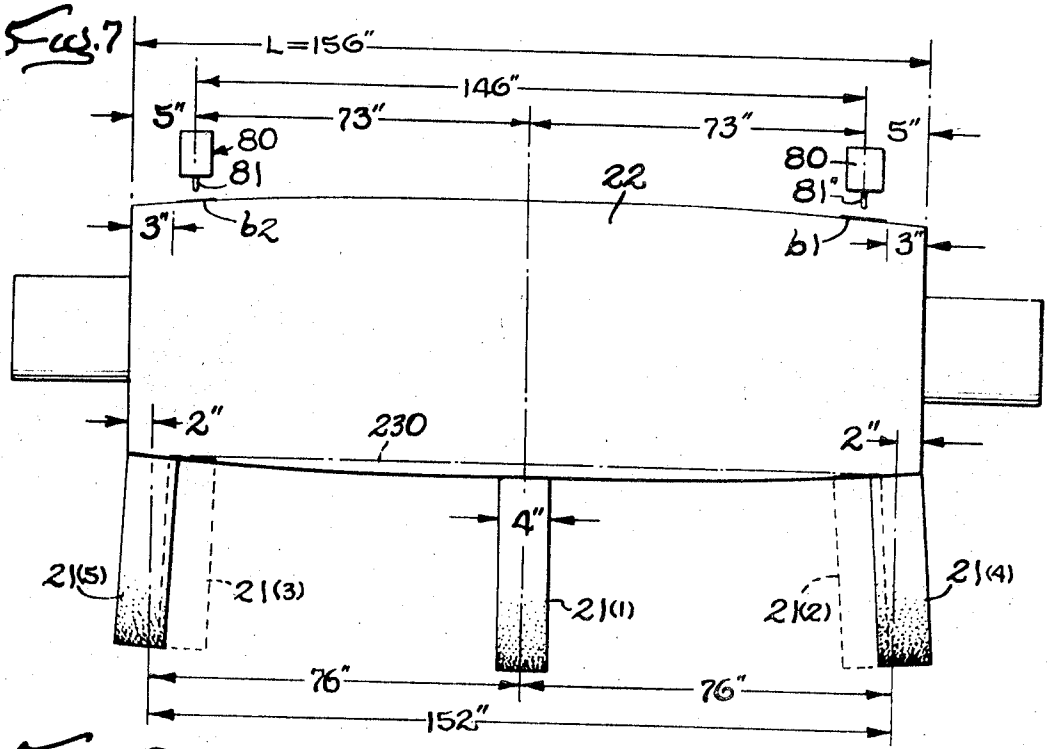


Fig. 8

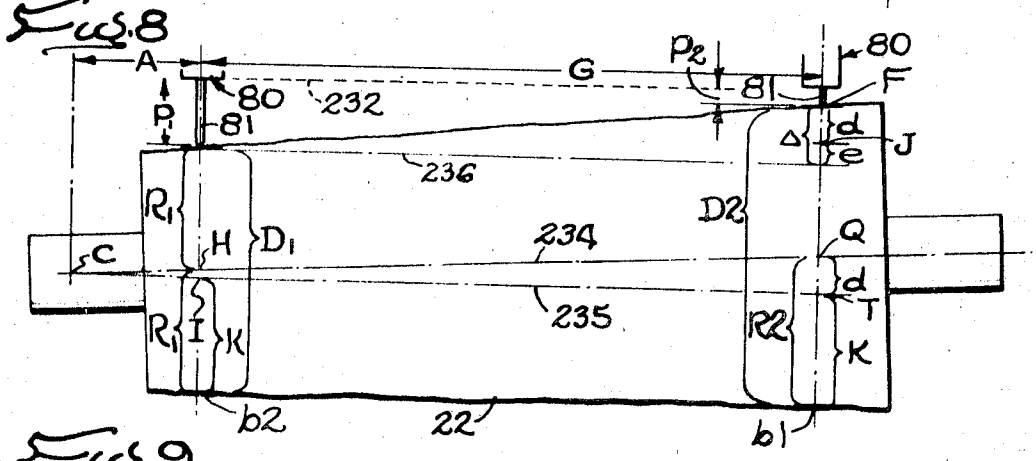
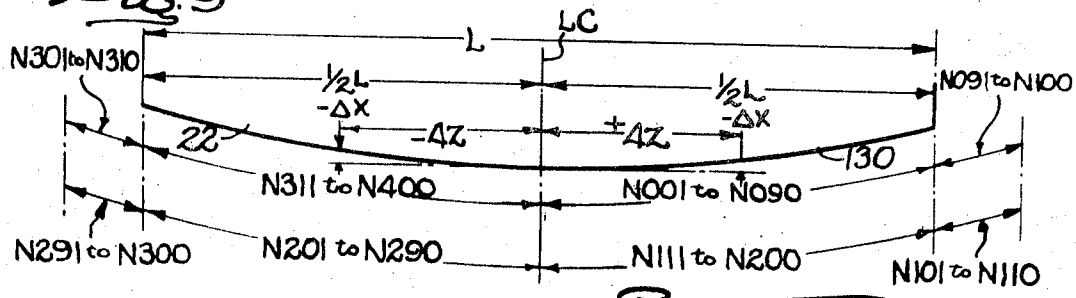
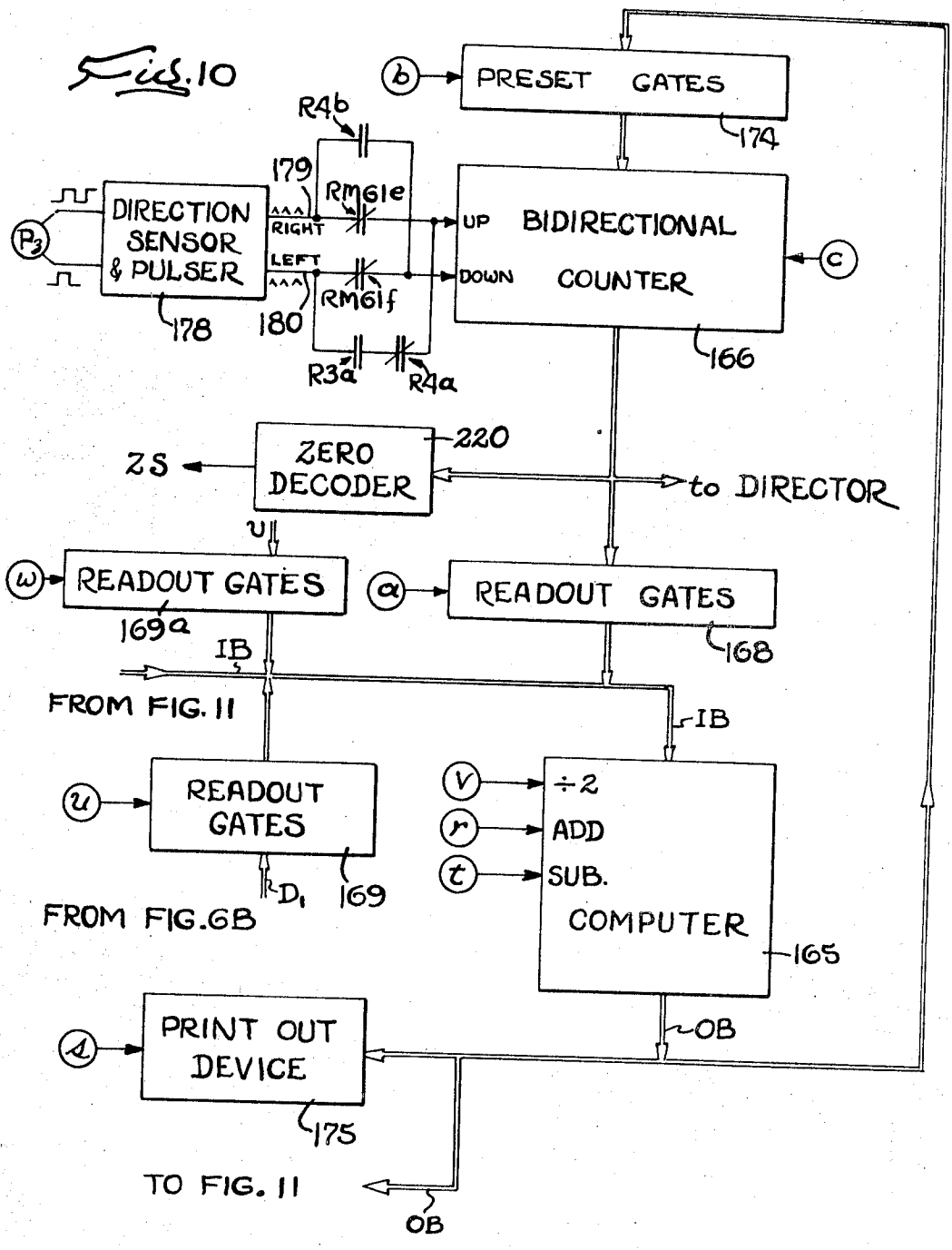


Fig. 9



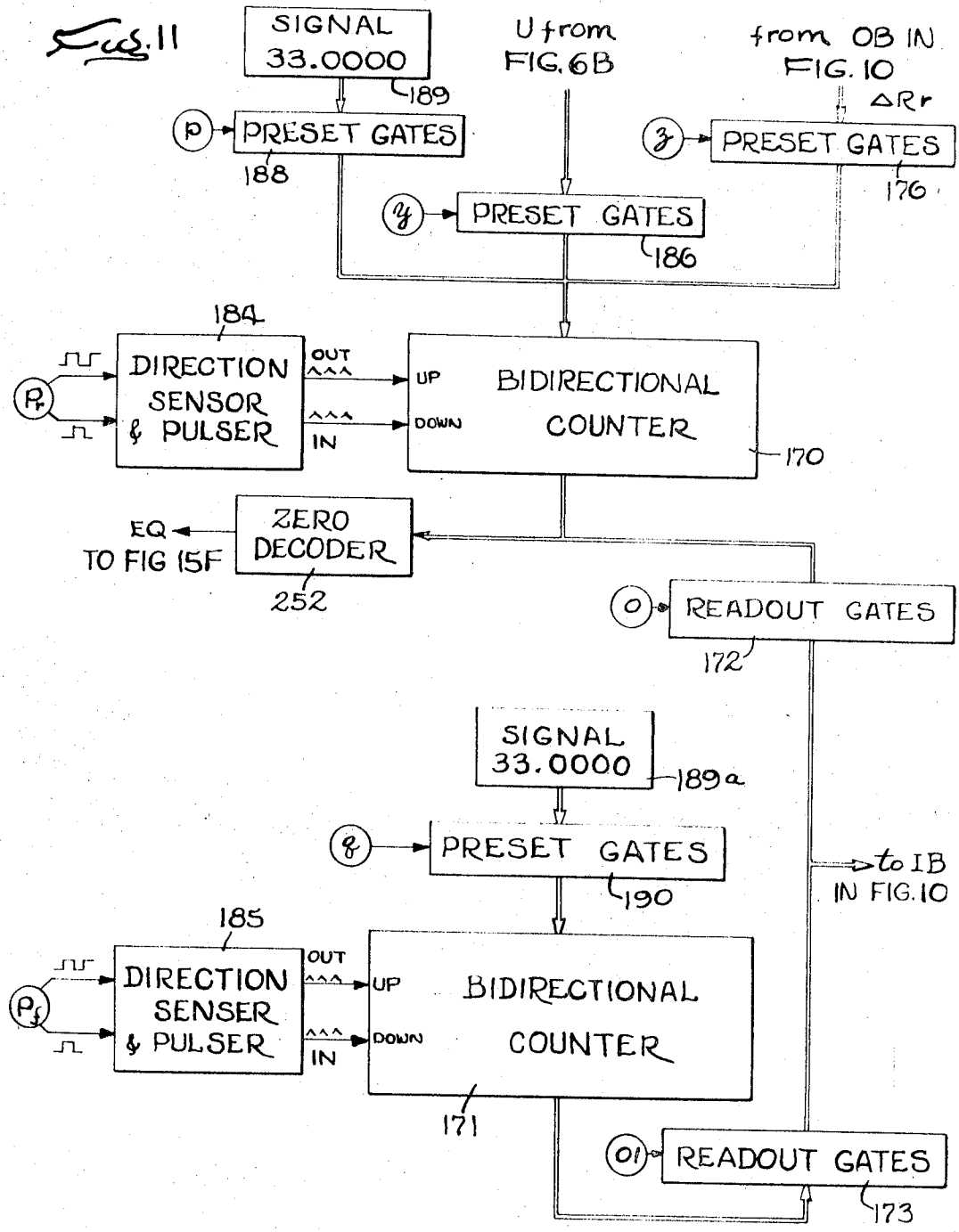
INVENTOR
Stephen C. Clark, jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

Fig. 10



INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

Fig. 11



INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

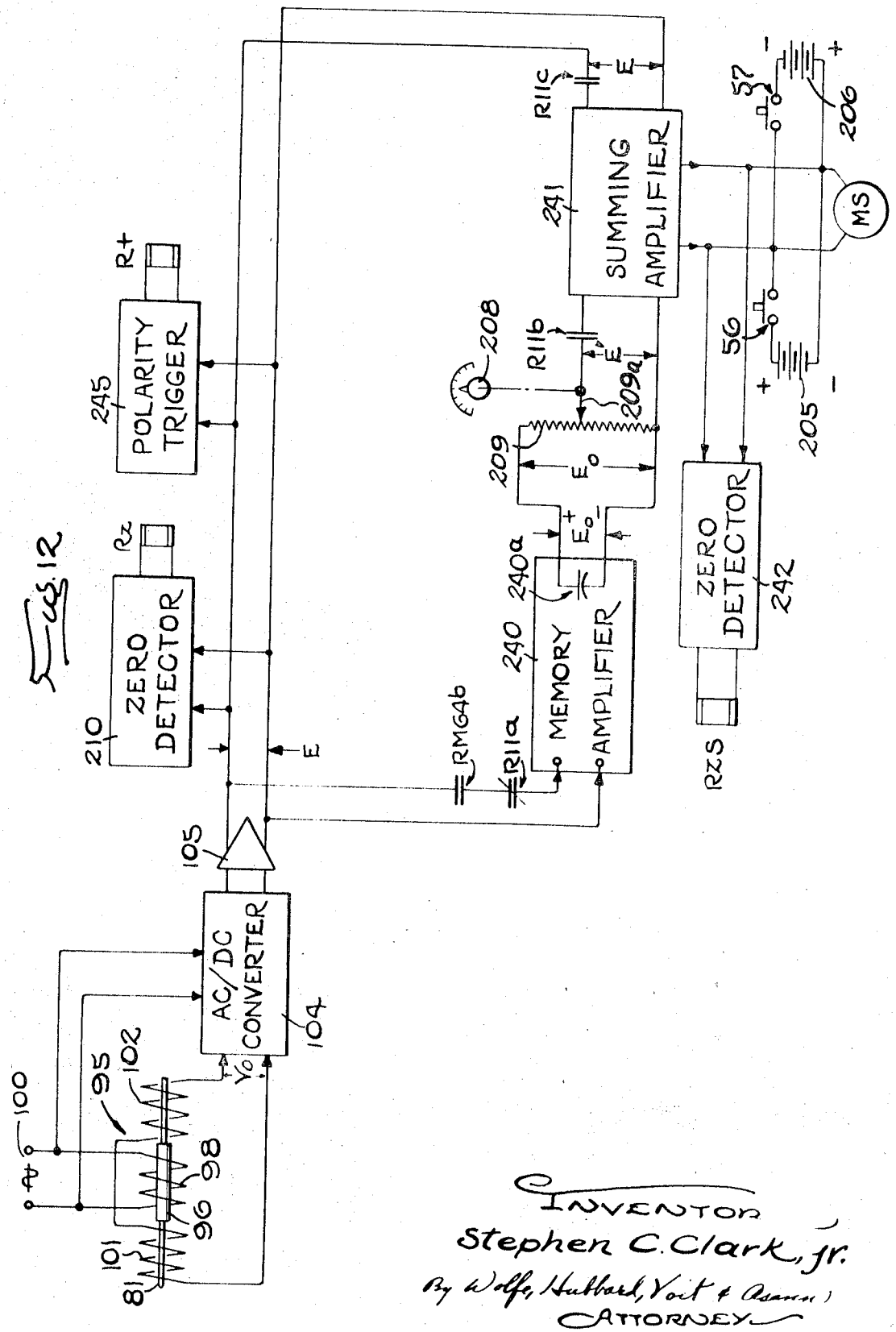


Fig. 12

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

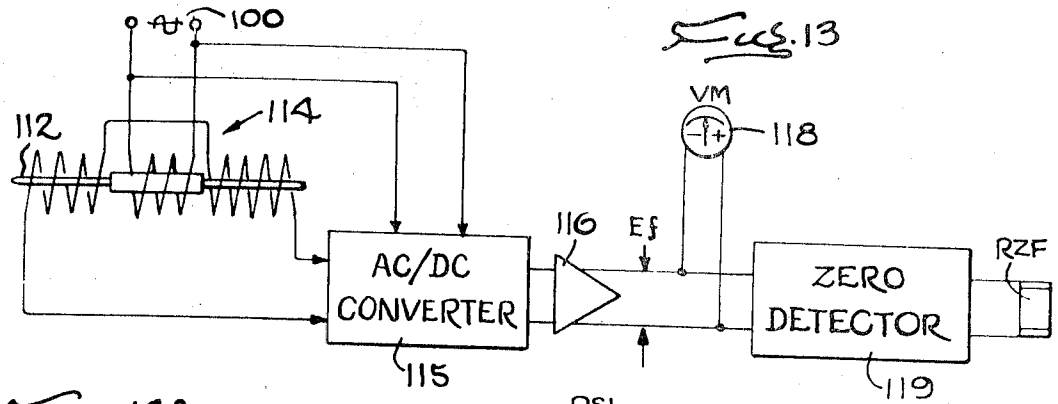


Fig. 13

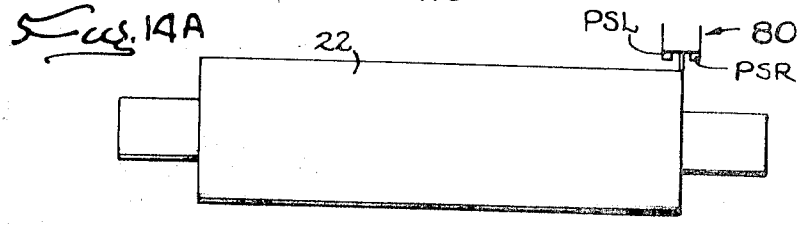


Fig. 14A

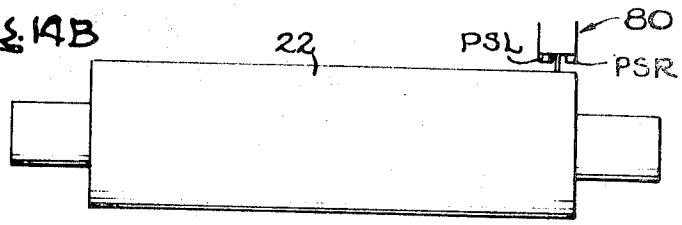


Fig. 14B

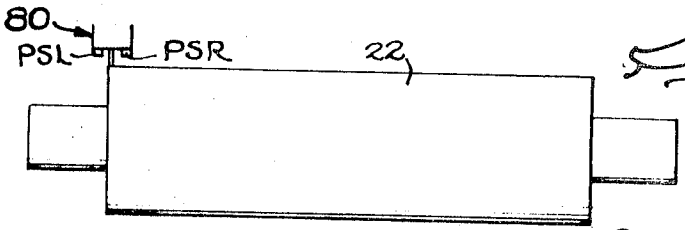


Fig. 14C

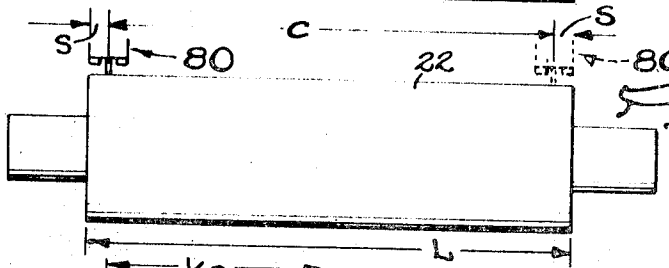


Fig. 14D

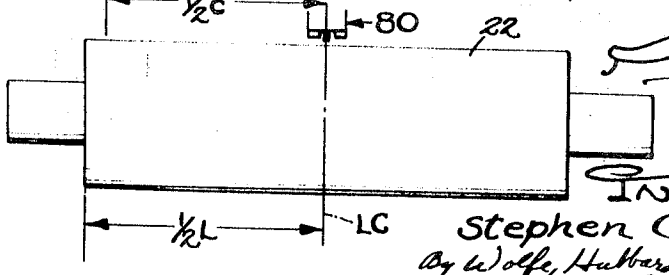
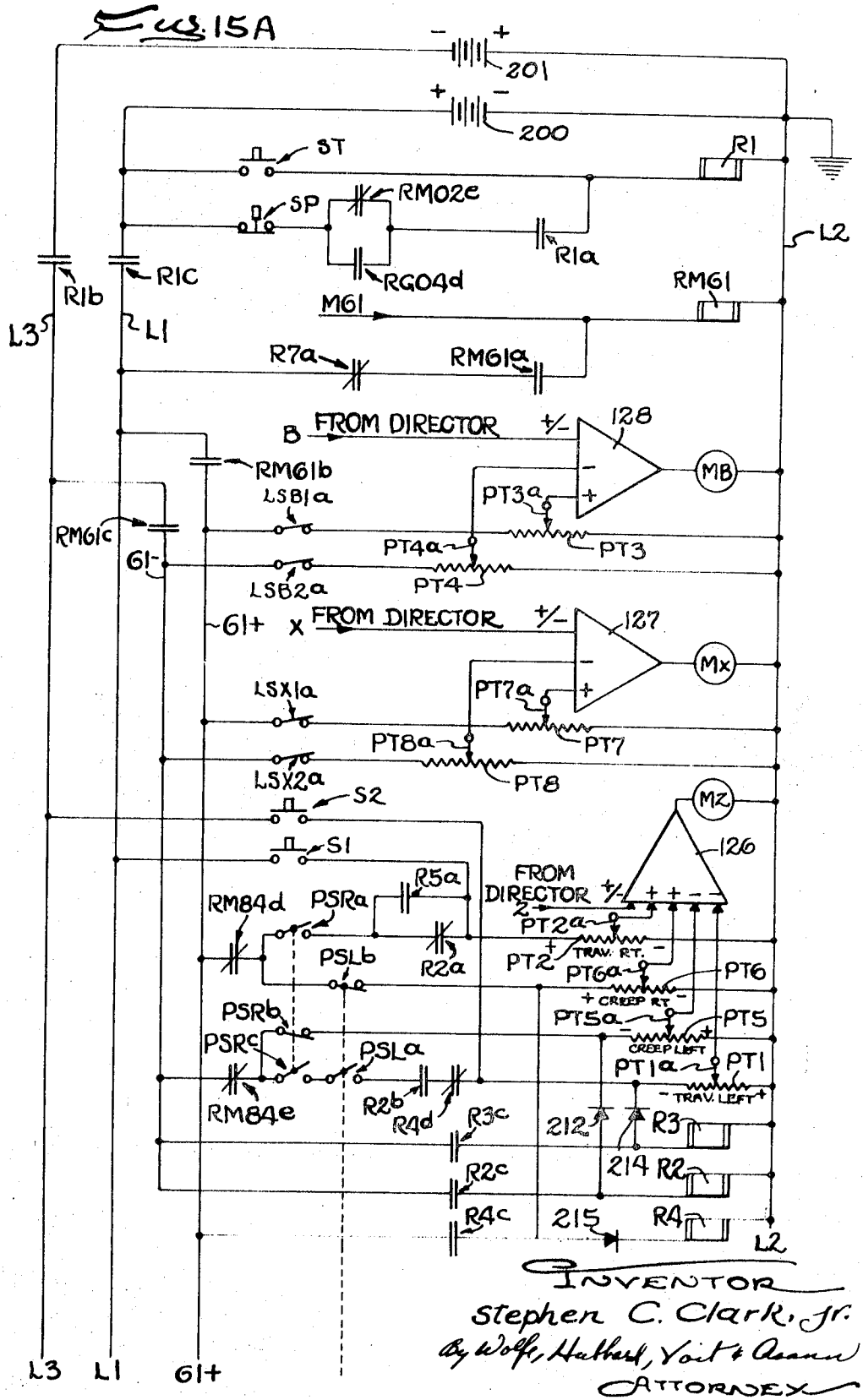


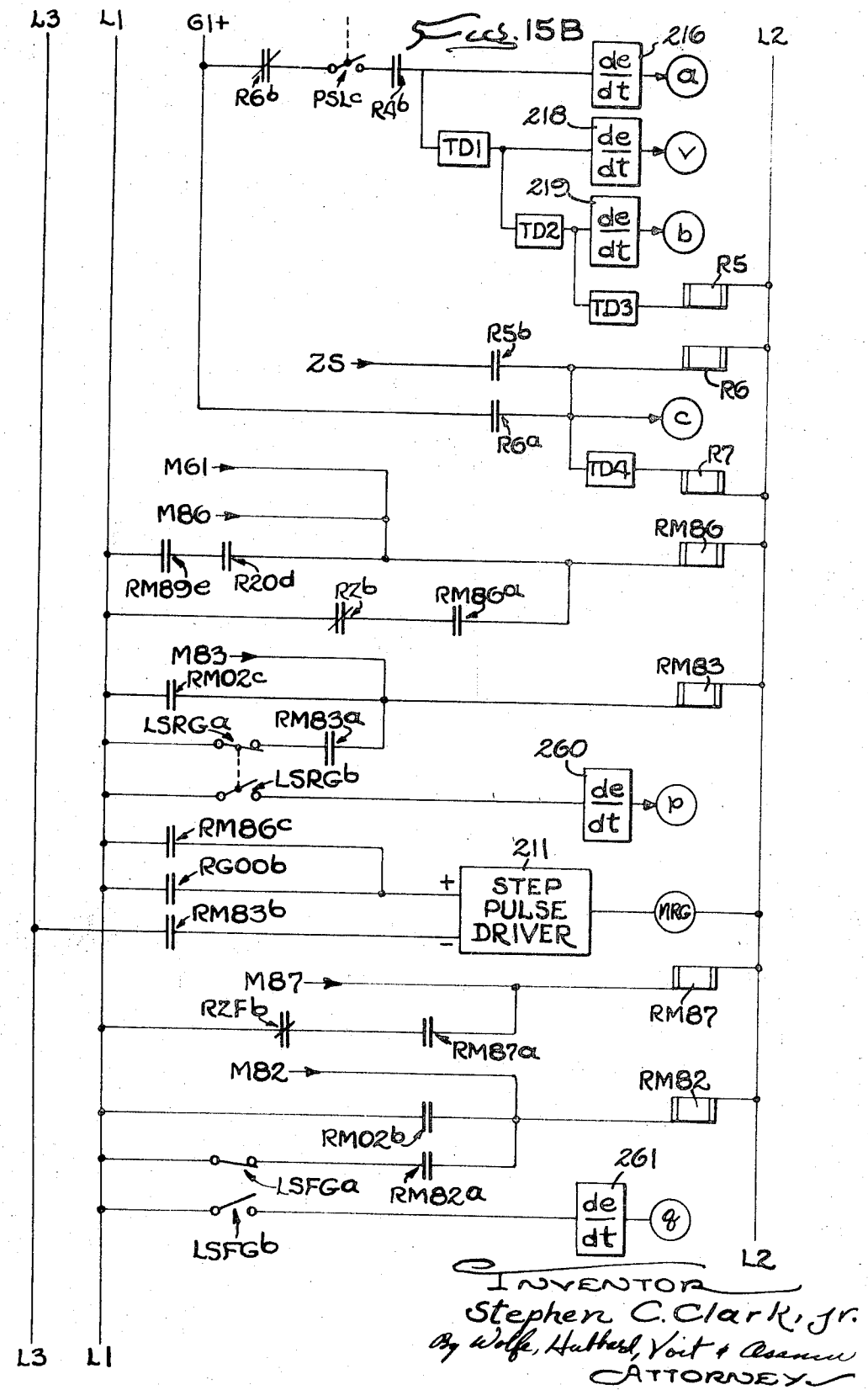
Fig. 14E

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

Fig. 15A



INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY



INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

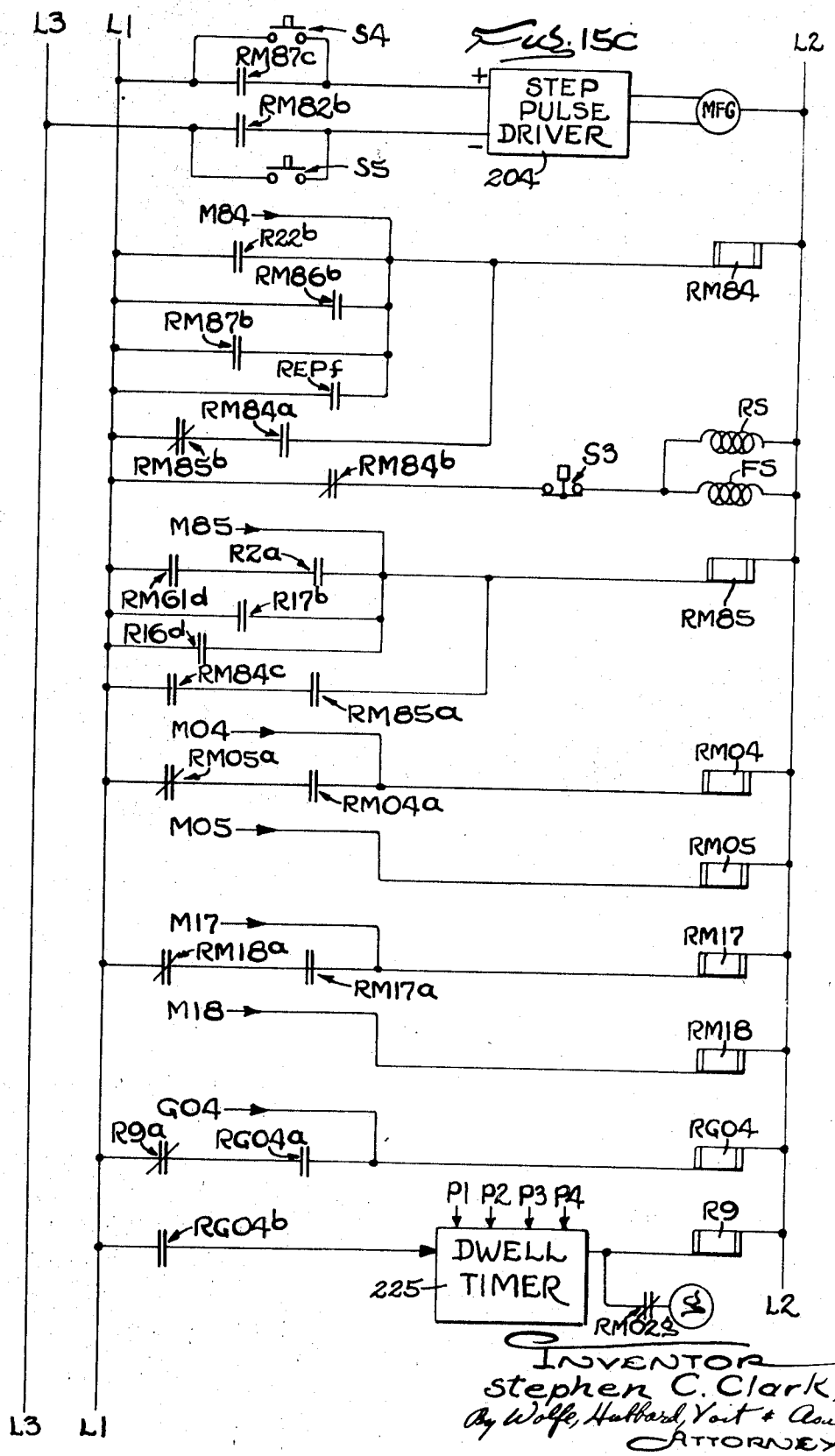


Fig. 15C

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

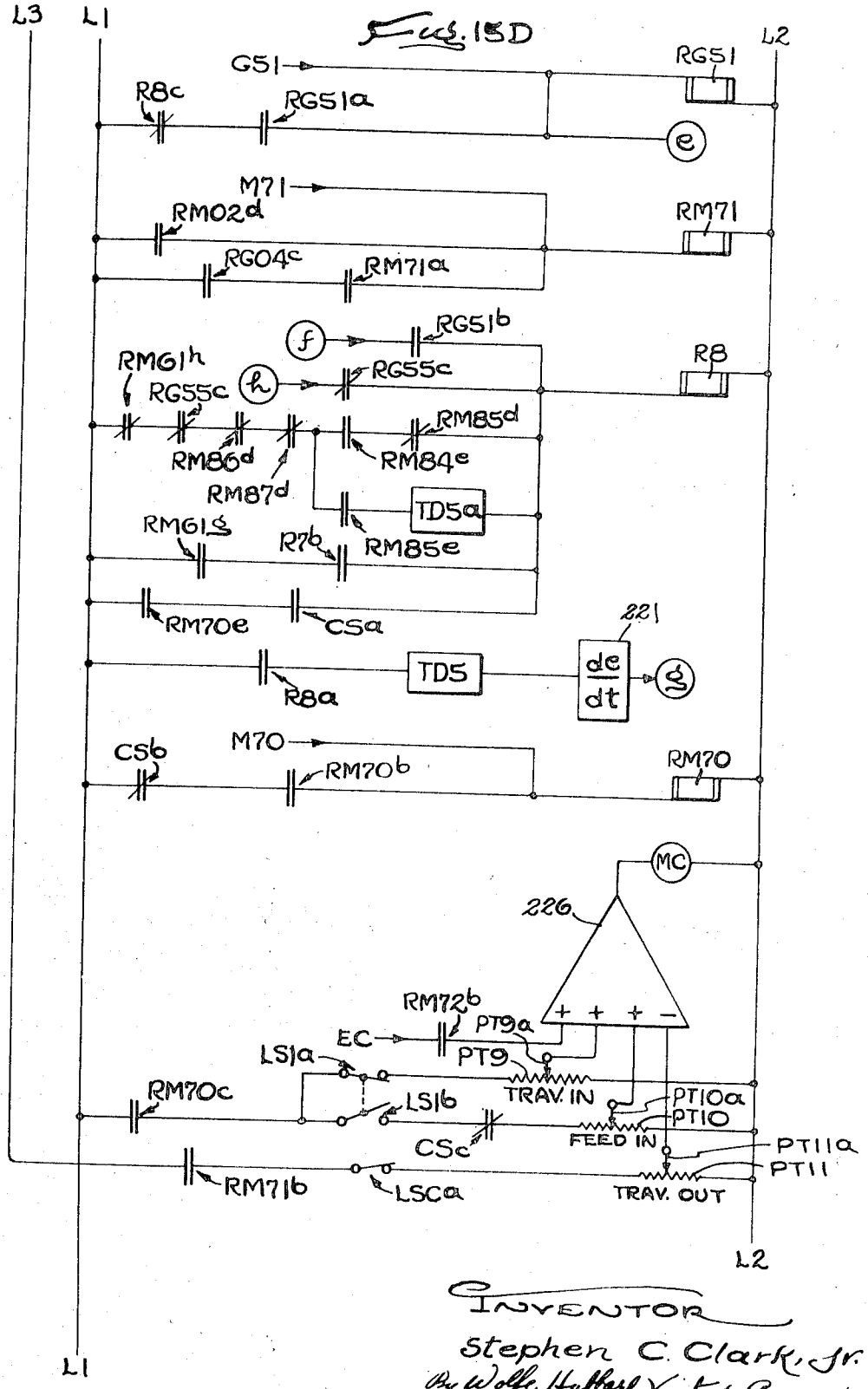


Fig. 15D

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

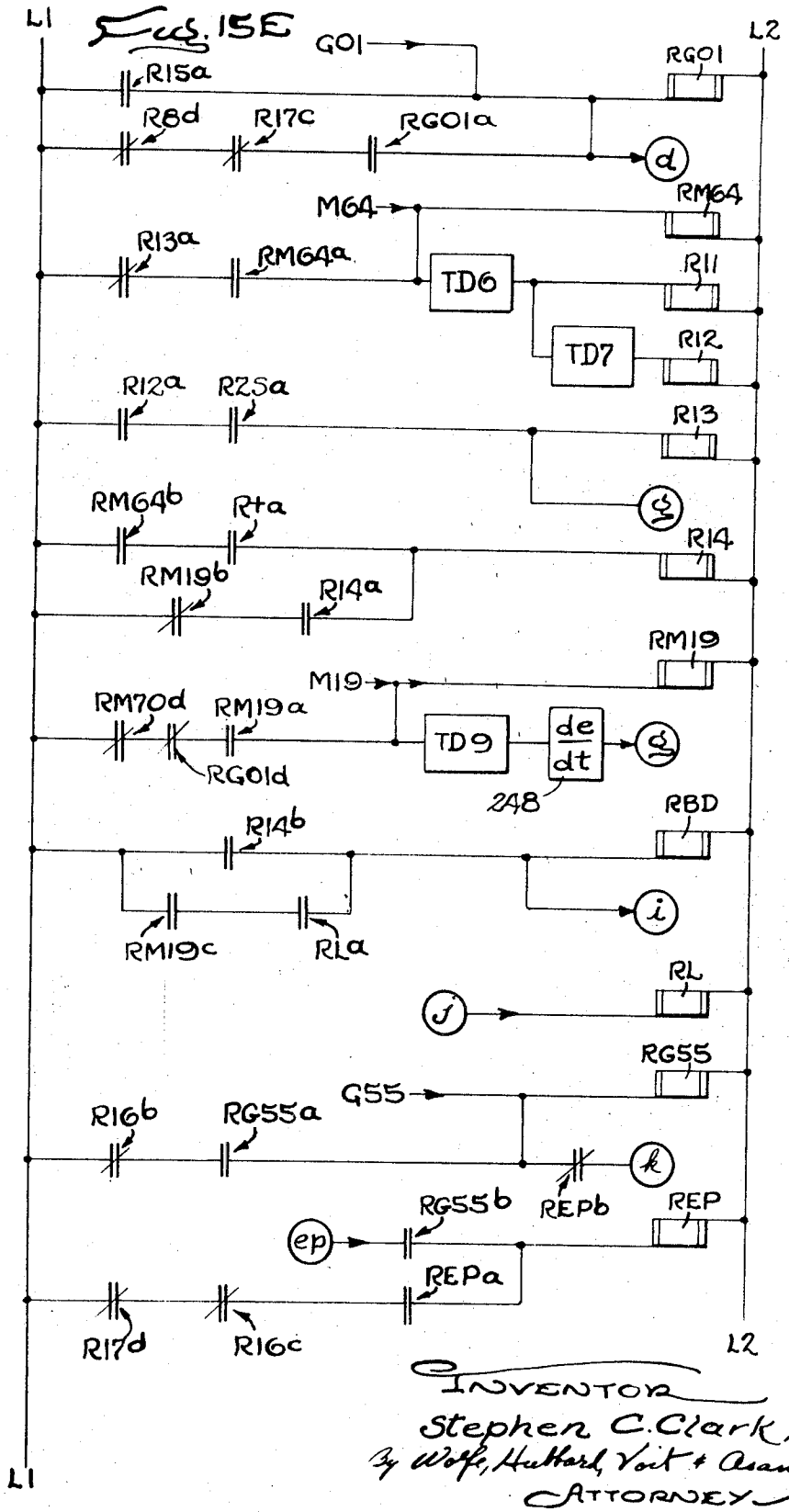


Fig. 15E

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

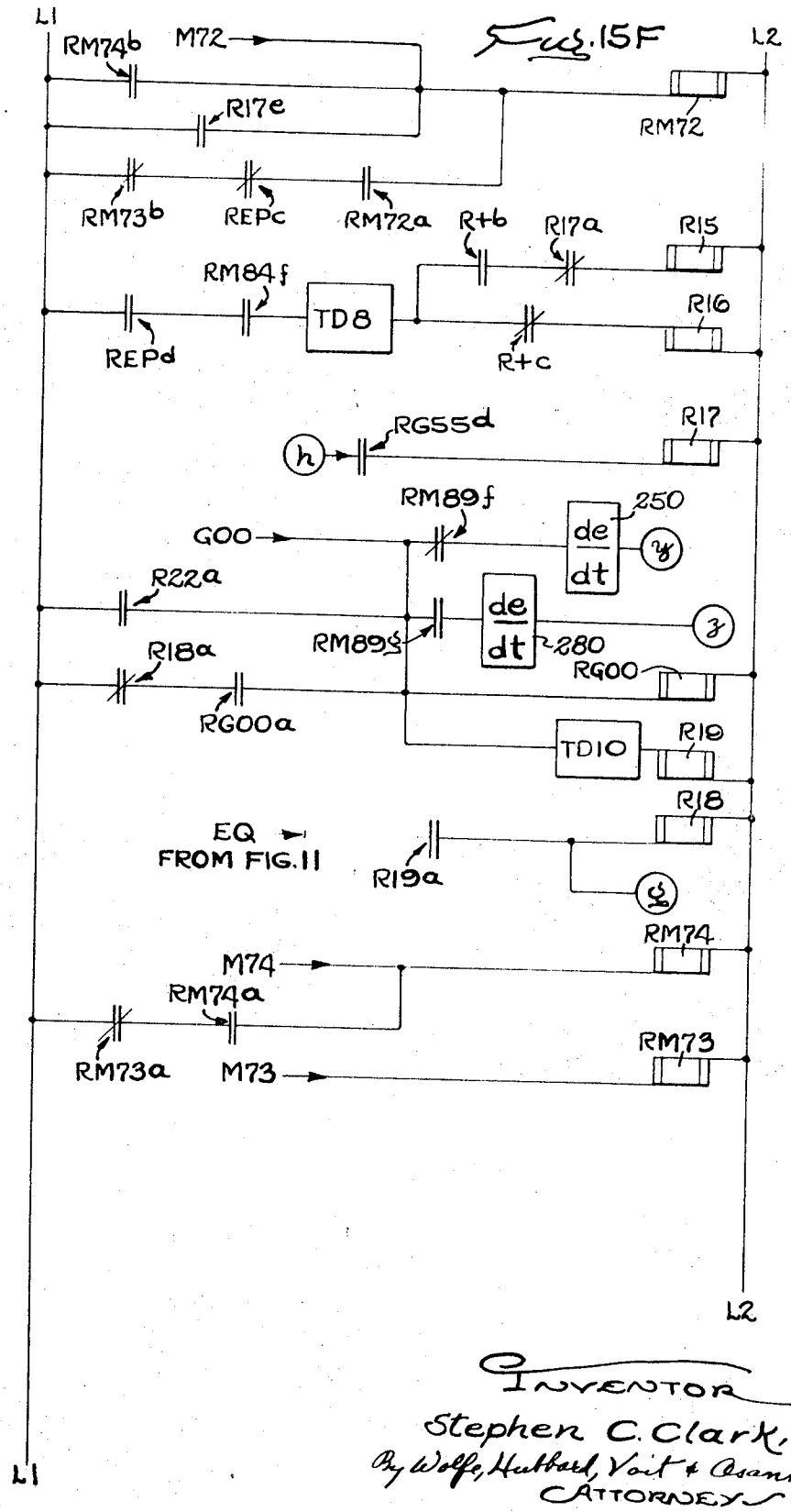


Fig. 15F

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

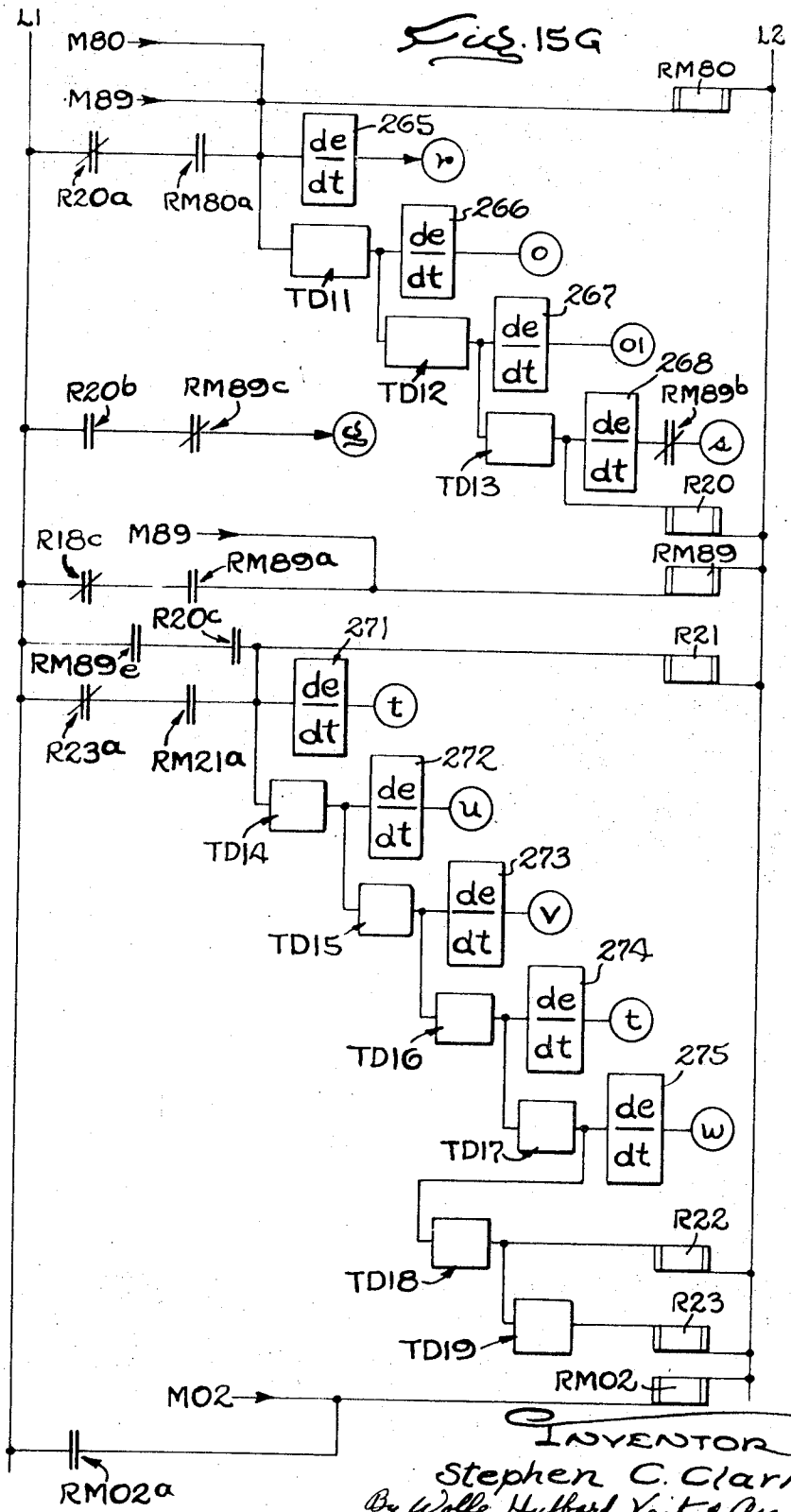


Fig. 15G

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEY

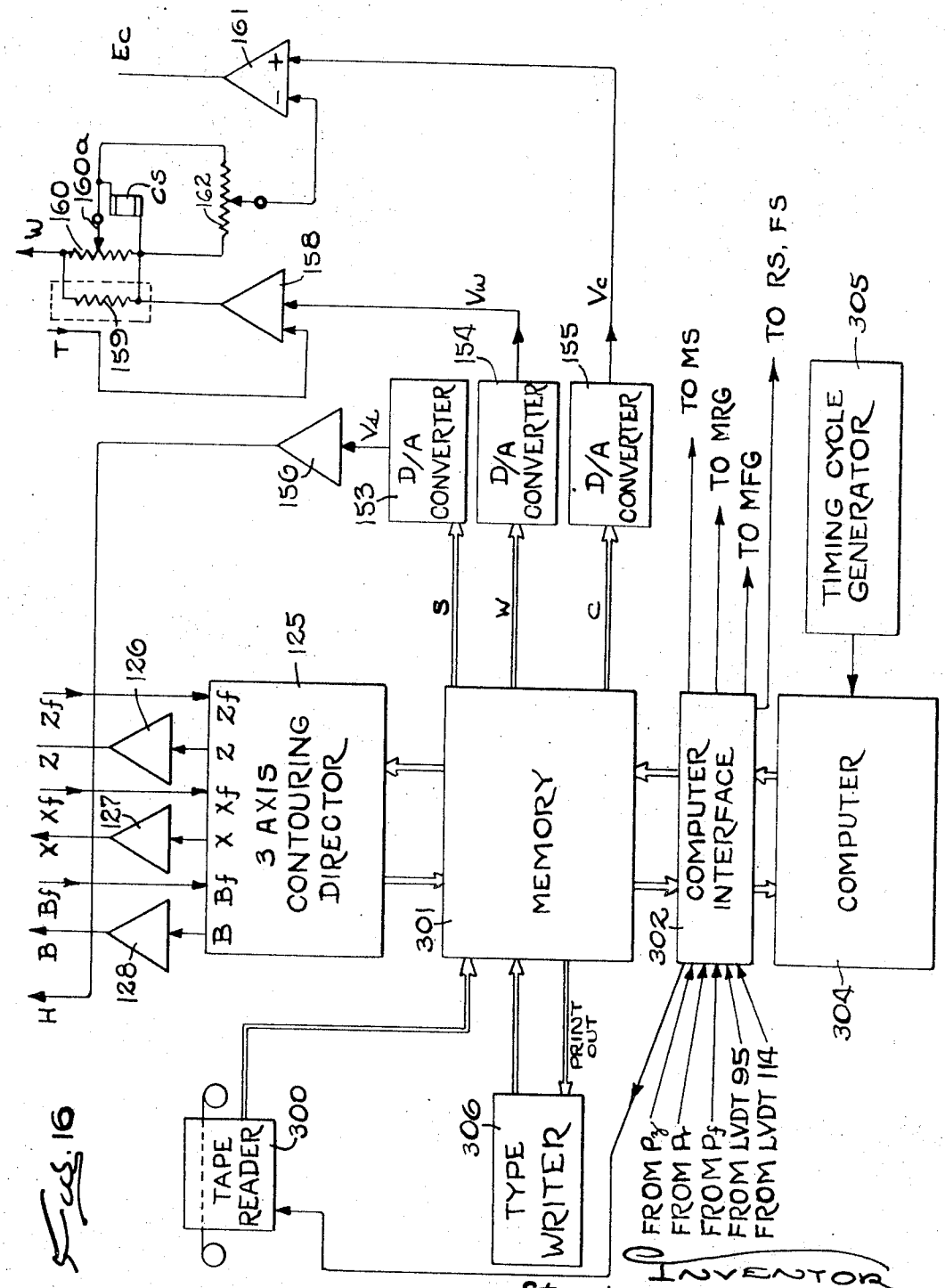


Fig. 16

INVENTOR
Stephen C. Clark, Jr.
By Wolfe, Hubbard, Voit & Osann
ATTORNEYS

METHOD AND APPARATUS FOR TURNING WORKPIECES AND UTILIZING PROGRAMMED DATA

TABLE OF CONTENTS

	Column page
Abstract of the Disclosure	Front
Cross-Reference to a Related Application	1
Background of the Invention	2
Summary of the Invention	2
Brief Description of the Drawings	3
Description of Preferred Embodiments	4
A. An Exemplary Machine Tool	4
B. Control Instrumentalities on the Grinding Machine	6
1. Feedback Pulse Generators	6
2. Steadyrest Servomotor	7
3. Sensing Switches	7
4. Probe Assemblies	8
5. Proximity Switches	9
C. The Control System in General	10
1. Contouring Apparatus	10
2. Sequence Command System	13
3. Data Manipulation Apparatus	14
D. Methods and Apparatus for Grinding a Roll	15
1. Setup Procedure	16
2. Location of Lengthwise Center; M61	18
(a) Movement of the Swivel Base to the Center of B Axis Travel	18
(b) Setting the Platform 35 to the Center of X Axis Travel	19
(c) Movement of Proximity Switches to Operative Positions	19
(d) Movement of Wheel to Center of Roll	20
3. Automatic Alignment of the Roll Axis	24
(a) Startup Operations	24
(b) Movement to Location of First Gaging Band	26
(c) Bringing the Wheel into Touching Contact with the Roll	28
(d) Grinding Right Gage Band to Predetermined Depth	28
(e) Movement of Wheel to Location of Left Gage Band	29
(f) Grinding of the Left Gaging Band	30
(g) Retraction of the Wheel Free of the Roll	30
(h) Sensing the Location of the Left Gaging Band on the Rear Side of the Roll	31
4. Determining Direction of First Grinding Pass; Initial Grinding	37
(a) Right End Larger	38
(b) Left End Larger	39
(c) Status of the System Prior to First Grinding Pass	40
(d) First Grinding Pass and Continuous Passing	41
(i) Case I—Material Removal Incomplete	42
(ii) Case II—Material Removal Complete	43
5. Rough Grinding	43
6. Finish Grinding	45
7. Sensing and Signaling the Roll Diameter	46
8. Cleaning Up the Roll Surface by Sparking Passes	50
9. Polishing Passes	52
E. Grinding a Second Roll to the Same Diameter	54
F. An Alternative Embodiment	58

CROSS-REFERENCE TO A RELATED APPLICATION

This application is a division of my copending application, Ser. No. 790,323, filed Jan. 10, 1969.

BACKGROUND OF THE INVENTION

The present invention relates in general to methods and apparatus for the machining of workpieces, and while it will find advantageous use in the operation of various machine tools, the invention is adapted to be applied with special advantages in the operation of grinding machines for shaping or renewing the shape of rolls such as those employed in metal rolling mills.

In the operation of large installations for the rolling of steel or aluminum into thin sheets or strips for coiling, the high inter-roll pressures and roll speeds result in severe wear of the surfaces of the individual rolls. The wear is often non-uniform, and any roll surface irregularities result in magnified surface imperfections in the sheets or strips. It is common practice to change the rolls in a given mill stand frequently, as often as once per eight hour shift. When each worn roll is removed from the mill, there is a need to have its surface re-finished or re-ground to nearly perfect smoothness and with the desired cylindrical shape (which may be a convex or concave contour lengthwise of the roll to compensate for roll loading pressure and produce a desired cross sectional shape in the rolled strip). To keep a large mill, and the investment which it represents, operating efficiently, it is desirable to re-grind worn rolls not only quickly so that they may be returned to service, but also with precision.

The increasingly severe shortage of skilled machinists leads to the result that manual control of grinding machines offers little prospect of satisfying the current demand for rapid and precise grinding of rolls. The present invention aims to overcome that difficulty by making roll grinding operations substantially fully automatic through the use of pre-calculated, programmed data of two kinds, viz., profile data which define the contour of the finished roll surface, and sequence commands which call for the execution of different routines in succession, and with preselected operating parameters. The need for a machinist of extreme skill is thus obviated and the speed with which any roll can be completely reground is increased beyond that attainable by even the most skilled operator.

SUMMARY OF THE INVENTION

A principal object of the invention is to provide methods and apparatus for the machining of workpieces to desired contours and surface finishes by a succession of operations carried out automatically in sequence, and all defined in advance by programmed data. In particular, it is an object to utilize a program of successive instructions defining successive multi-axis movements which make up a desired contour or profile, and which may be followed in the machining of a plurality of workpieces which are to have the same finished profile; and in conjunction with such a profile program, to utilize a program of sequential commands, prepared individually for each workpiece or a group of identical workpieces so as to bring about the desired sequence of successive operations, including calling out and using all or a part of the profile program when that is required in the machining of the workpiece.

It is another object of the invention to facilitate the use of the same program of profile data in the shaping of surfaces of a plurality cylindrical workpieces such that the surface contours are symmetrical about the lengthwise centers of the workpieces, even though the exact length of any particular one of the workpieces is not known or measured and the axial placement of the workpiece in a numerically controlled grinding machine is not determined by a painstaking and time-consuming setup procedure.

In a more specific sense, it is an object of the invention to eliminate the need for a long and detailed numerical program to be prepared (and represented on an individual punched tape, according to current practice) for each individual specific workpiece in a series of workpieces which are to have the same final profile but which are to be made with different final sizes (e.g., lengths or diameters), and a related object is to provide methods and apparatus by which (a) a single profile program of numerical instructions is used with any one of a

number of sequence command programs to produce any of a family of workpieces having the same shape but different final sizes or dimensions, or (b) a single sequence command program is used with any one of a number of profile programs of numerical instructions to produce any of a family of workpieces having the same final size or dimensions but different profiles or contours. In the first case (a), to change a machine's production from a given one to another of the family of workpieces, it is only necessary to use a different pre-prepared sequence program stored, for example, on a punched tape; and in the second case (b), to change a machine's production from a given one to another of the family of workpieces, it is only necessary to use a different pre-prepared profile program stored, for example, on a punched tape.

In carrying out the invention, the commands contained within the sequence program are executed in succession, and when in the sequence of operations it is necessary to cause the tool to follow all or a part of the contoured profile, a sequence command brings the profile program into operation and defers the execution of the next sequence step until the successive blocks of profile program have been executed in succession to bring the tool to a particular location or until a designated profile block has been executed. A major advantage of the invention is the switching back and forth for control of a machine tool according to either a sequence program or a separately stored profile program, either program being readily and conveniently changed without re-calculating or replacing the other.

The foregoing summary of the invention and the advantageous objectives achieved thereby will be better understood after consideration of the more detailed description of a specific, exemplary embodiment of the methods and apparatus. And additional advantages will also become apparent as the detailed description proceeds with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the attached drawings:

FIG. **1** is a fragmentary plan view, partly in diagrammatic form, of an exemplary grinding machine;

FIG. **2** is a vertical section taken substantially along the offset line **2—2** of FIG. **1**;

FIG. **3** is a diagrammatic illustration of the spacial relationship of two probe assemblies and a roll in the grinding machine;

FIG. **4** is a diagrammatic cross section showing the basic organization of the two probe assemblies;

FIG. **5** is an end view, taken substantially along the line **5—5** of FIG. **4**, of the rear probe assembly and showing the relationship of two proximity switches carried thereby;

FIGS. **6A** and **6B**, when joined to match the correspondingly labeled lines, constitute a block diagram of an exemplary control system associated with the grinding machine which is diagrammatically illustrated for ease of understanding;

FIG. **7** shows a typical workpiece or metal roll to be shaped in the grinding machine, and dimensions assumed by way of example merely for purposes of explanation;

FIG. **8** illustrates roll having unequal diameters at points spaced symmetrically from its lengthwise center, e.g., tapered, the axis of which is initially misaligned relative to the longitudinal path of wheel travel in the machine;

FIG. **9** is a fragmentary plan view of a roll having a convex profile, and with legends indicating the numerical programming of blocks of data to define the profile;

FIG. **10** is a block diagram illustrating apparatus which forms a part of the control system, and particularly that portion which processes signals to perform certain arithmetic functions;

FIG. **11** is a block diagram showing bidirectional counters associated with the front and rear probe assemblies, and devices for supplying input signals thereto or taking output signals therefrom;

FIG. **12** is a diagram, partly in schematic and partly in block form, showing the rear probe transducer and the manner in which its signal is utilized in aligning a roll axis in the grinding machine;

FIG. **13** is a block diagram showing the front probe transducer and the devices which respond to its signal;

FIGS. **14A** through **14E** are a series of simplified, diagrammatic plan views showing the position of the rear probe assembly at various stages in the routine of finding the lengthwise center of a roll placed in the machine;

FIGS. **15A** through **15G**, when joined to match the vertical lines L1 and L2 therein, collectively form a schematic diagram of control circuitry which is associated with the apparatus shown in FIGS. **6A** and **6B** to carry out various routines designated by sequence commands; and

FIG. **16** is a block diagram which when joined to FIG. **6A** in lieu of FIG. **6B** illustrates an alternative system embodying the apparatus of, and for carrying out the method of, the invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

A. An Exemplary Machine Tool

Referring now to FIGS. **1**, **2** and **6A**, a grinding machine **20** is there shown as a specific example of the general class of machine tool which is to be controlled in the practice of the present invention, and the term "grinding" used herein is to be taken as a concrete example of the more generic term "cutting" which designates removal of material from a workpiece. Although the invention may be applied to good advantage in turning machines such as lathes having metal cutting tools for shaping generally cylindrical workpieces, the description which follows will refer for the sake of concreteness to the grinding machine **20** which has an abrading tool, specifically a rotationally driven grinding wheel **21**, for shaping and finishing the surfaces of workpieces, such as metal rolls **22** of the type employed in rolling mills. Either when such a roll is first manufactured, or at frequent intervals during its useful life, it is necessary to shape and smooth the roll surface. The quality of the rolling mill product, and the efficiency of a rolling mill set-up require that the contour and surface finish of a roll be precise, and that the machining of the roll be effected in the shortest feasible time and with a minimum of skilled labor involving manual measurements or adjustments. Most frequently, such generally cylindrical rolls are not to be shaped with a truly cylindrical surface, but are given a lengthwise contour which may be concave, convex (as shown in FIG. **7**), or even with predetermined lengthwise undulations (e.g., quarter reliefs). While in many of the figures and in portions of the description which follows the roll is treated as being cylindrical, it is to be understood that this is in the interest of brevity, and that either a truly cylindrical or a contoured roll is contemplated.

The grinding machine **20** conventionally includes journaling supports for rotatably supporting the roll **22**. As here shown in FIGS. **1**, **2** and **6A**, a tailstock **24** (adjustable in a lengthwise direction along the ways **25** of a base **26** to accommodate rolls of different lengths and a steadyrest **28** receive the "neck" or stub shaft at the right end of the roll. The left "neck" of the roll is supported in a left steadyrest **29** adjacent a headstock **30** and is drivingly connected by a clamp **31** to the output shaft of the headstock. Rotational driving power is supplied to the headstock by belts **32** driven from a headstock motor MH controllable in its speed so that the roll **22** may be rotated at a desired speed during grinding operations.

To act upon the surface of the roll **22**, the grinding wheel **21** is mounted not only such that it can be rotationally driven at high speed, but also such that it can be moved or positioned along a plurality of elementary paths, conventionally called machine "axes," relative to the roll **22**. Briefly stated and as shown in FIG. **6A**, the wheel **21** may be moved to the right or left lengthwise of the roll, such movement being here labeled and designated as positive or negative motion along a Z axis.

The wheel is mounted also for bodily swiveling movement about a vertical pivot, so as to keep the wheel face substantially parallel to a crowned or contoured rolled surface (see FIGS. 6A and 7). Such swiveling motion in a counterclockwise or clockwise direction is here labeled and designated as positive or negative B axis motion. Finally, the wheel is mounted for movement inwardly and outwardly relative to the roll 22, i.e., in a direction transverse to the Z axis and thus transverse to the longitudinal dimension of the roll. This motion of the wheel is here labeled and designated as negative and positive movement along an X axis.

The wheel 21 is itself fixed to a shaft 34 journaled for rotation on a movable member or platform 35 and connected by driving belts 36 to a wheel motor MW which is variable or controllable in speed. A tachometer 38 may be driven from the shaft of the motor MW to supply a speed feedback signal which is used to stabilize the control of the wheel motor speed, as noted below. Thus, while the motor MW is energized and the wheel 21 rotationally driven during most of the operations of the grinding machine, it is the movements of the platform 35 along the Z, B and X axes which result in the wheel being moved along a desired path in contact with the surface of the roll to grind the latter to a desired shape and finish.

The platform 35 is superimposed on a cross slide 40 resting upon a swiveling base 41 supported on a main carriage 42 which rests upon a primary base 44. To accomplish movement of the wheel 21 along the Z axis, the main carriage 42 is slidable along the ways 45 of the main base 44 and contains a nut 43 engaged with a precision lead screw 46 driven in one direction or the other by a reversible, variable speed motor MZ. As the motor drives the lead screw 46 in one direction or the other, the carriage 42 moves to the right or the left along the Z axis and the wheel 21 is thus translated in a direction substantially parallel to the longitudinal axis of the roll 22.

The swiveling base 41 rests upon the carriage 42 with freedom to swing in a horizontal plane about a vertical pivot 48 (FIG. 1). To swing the base 41 and impart B axis motion to the wheel 21, a variable speed, reversible servomotor MB is connected via a worm 49 and a worm wheel 50, which is internally threaded to form a nut engaged with a lead screw 51, to a wedge 52. One or more biasing springs 54 urge the swiveling base 41 a clockwise direction about the pivot 48 so that a wedge-following roller 55 is kept in contact with the inclined surface of the wedge 52, the opposite surface of the wedge bearing against and being slidable relative to back-up pins or wheels 56 fixed to the main carriage 42. As the motor MB is turned in one direction or the other, and the wedge is thus translated lengthwise, camming action on the roller 55 results in the swiveling base 41 being rotated or rocked in one direction or the other along the B axis about the pivot 48. Such B axis motion is employed to bring the wheel to various angles relative to the Z axis, and so that the wheel face is maintained substantially parallel to a curved or contoured roll surface as illustrated by various positions of the wheel shown in FIG. 7. The B axis motion need have a range of only a few degrees to accommodate rolls which conventionally have only slight lengthwise curvatures or contours, but such slight swiveling movement of the wheel is important to provide finished rolls with the necessary precise contours.

To provide a first component of motion of the wheel inwardly or outwardly relative to the roll 22 disposed in the machine, the cross slide 40 rests upon and is slidable along ways 58 formed on the swiveling base 41. A variable speed, reversible motor MC is connected through a right-angle gear transmission 59 to a lead screw 60 engaged with a nut 61 on the cross slide 40, so that by controlled energization of the motor the wheel can be moved bodily toward or away from the roll. While the movement produced by the motor MC and the cross slide 40 is transverse to the Z axis and thus along the X axis, such motion is not used in the present instance for purposes of controlled grinding of the rolled surface. Thus, as a matter of convenience, the movement of the cross slide inwardly or outwardly is here designated as negative or positive motion along a C axis. Movement along the C axis is tantamount to motion along the X axis, but it is produced by a motor MC which is separate and apart from that which causes controlled X axis motion.

The wheel platform 35 is supported on the cross slide 40 with freedom to rock or tilt about the horizontal axis of a pivot bearing 64 (FIG. 2). The weight of the platform keeps its front portion (furthest from the roll) biased downwardly in contact with a wedge 65 which has threaded engagement with a lead screw 66 connected to a variable speed, reversible gear motor MX. As the motor turns the screw 66 in a negative or a positive direction, the wedge 65 is driven inwardly or outwardly to rock the platform upwardly or downwardly about the pivot bearing 64, thereby moving the surface of the wheel 21 inwardly or outwardly relative to the roll surface. Although the wheel is bodily moved along an arcuate path in response to operation of the motor MX, the radius of the arc is relatively large and the extent of the bodily arcuate movement of the wheel is always relatively small. Thus, the tilting motion of the platform 35 and the wheel 21 may properly be assumed as constituting movement of the wheel in a direction transverse to the Z axis of the machine and thus along what has here been termed as the X axis. While the extent of X axis motion need not necessarily be limited, in most roll grinding machines, it is sufficient if the range of X axis travel be on the order of 0.100 inch, since the depth of concave or convex contours to be imparted to rolls for conventional rolling mills is never more than this amount.

The manner in which each of the motors here described is controlled to produce the operations for the grinding of a roll will be described as the present specification progresses. It will be assumed that each such motor is a reversible, variable speed DC. motor, although other types of motors may, of course, be used.

For brevity and clarity in the present application, the terms "right" and "left" will be used to designate the tailstock and headstock ends of the grinding machine, and the ends of the roll which are respectively journaled in the right and left steadyrests 28 and 29. It is to be understood, however, that this is an arbitrary designation and that one may locate the headstock and tailstock of the grinding machine at the right and left ends, respectively.

Similarly, and merely as a manner of convenient designation, the "front" side of the roll 22 will be considered that side which is closest to the grinding wheel 21, and the "rear" of the roll will be considered that side which is diagrammatically opposite to the location at which the wheel 21 may be brought into engagement with the roll surface. Movements of the wheel toward the roll surface will be called "inward" motion, and movements of the wheel 21 away from the roll surface will be designated as "outward" motion.

B. Control Instrumentalities on the Grinding Machine

The motors MH, MW, MZ, MB, MC and MX are the drive means which receive motion or speed controlling signals from the control system to be described. Prior to that description, however, it will be helpful first to mention certain feedback or measuring instrumentalities provided on the machine to form a part of the control system.

1. Feedback Pulse Generators

It is a practice familiar to those skilled in the art of numerical control of machine tools to provide feedback devices which signal the displacements of the various movable members. In the present instance, conventional bidirectional feedback pulse generators are driven in timed relation to movement of each of the principal movable machine parts, such generators producing one pulse for each predetermined increment of movement, for example, one pulse for each 0.0001 inch of motion. It will be assumed here that each such pulse generator produces two trains of square wave pulses, one lagging or leading the other in phase when the motion is in one

sense or the other. In this way, feedback pulses from each of the generators can be determined as representing positive or negative motion.

As shown in FIG. 6A, pulse generators Pz, P*b* and P*x* are coupled to be driven from or in timed relation to the movements of the wheel **21** along the Z, B and X axes. As diagrammatically shown, the pulse generator Pz is coupled to the shaft of the motor MZ, and thus rotates with lead screw **46**, so as to supply output pulses indicative of movements of the main carriage **42** along the Z axis. Similarly, the pulse generator P*b* is connected to the worm **49** driven by the motor MB and supplies pulses indicative of movements of the swiveling base **41**, and thus of the wheel **21**, along the B axis. Finally, pulse generator P*x* is coupled directly to the output shaft of the motor MX and supplies output pulses indicative of movements imparted to the wedge **65**, and thus X axis motion imparted to the wheel **21**. No pulse generator is required in association with the motor MC and the movements which it imparts to the cross slide **40**.

2. Steadyrest Servomotor

As will be described later, the right steadyrest **28** is adjustable transversely of the Z axis of the grinding machine **20**, for the purpose of aligning the axis of a roll with the Z axis. As shown in FIGS. **2** and **6A**, a small reversible servomotor MS is coupled to drive a lead screw **68** which in turn will shift the steadyrest **28** forwardly or rearwardly in a direction transverse to the Z axis of the machine. Wen the motor MS is energized to so move the steadyrest **28**, the right end of the roll **22** will be pivoted in a horizontal plane about the point at which the left neck is supported in the left steadyrest. In this way, and as explained below in greater detail, the axis of the roll **22** may be brought into alignment or parallelism with the Z axis of the machine.

3. Sensing Switches

Several sensing switches, which may be small limit switches or their equivalents, are utilized for various purposes to be explained. For the present, it will suffice simply to identify the locations of these switches on the machine and the manner in which they are actuated.

As a means to signal when the swiveling base **41** is in the center of its range of B axis travel, a first pair of switches LSB1, LSB2 (FIG. **6A**) are disposed adjacent a camming member which moves with, or in timed relation with, the swiveling carriage. These two switches are mounted on the main carriage **42** with the actuating finger of the first switch disposed opposite a camming surface **69**, and the actuating finger of the second switch disposed opposite a camming surface **70**, formed on an arm **71** projecting from the wedge **52**. The switches are mounted so that both are actuated only when the swiveling base **41** is at the center of its B axis travel. If the base is located clockwise of its center position by the wedge **52**, then the camming surfaces **69** and **70** will hold the switches LSB1 and LSB2 respectively actuated and deactuated. On the other hand, if the swiveling base **41** is located counterclockwise of its center position, then the switches LSB1 and LSB2 will be respectively actuated and deactuated. With the base **41** in its centered position, both switches will be actuated.

Similarly, as a means to signal when the wheel platform **35** is positioned in the center of its X axis travel, a second pair of limit switches LSX1 and LSX2 are disposed to be actuated by camming surfaces **72**, **73** formed on a projection **74** fixed to or movable with the wedge **65**. The camming surfaces are shaped and located such that the switches LSX1 and LSX2 will be respectively deactuated and actuated if the platform **35** resides on the negative side of the midpoint of its X axis range of travel. Conversely, the switches LSX1 and LSX2 will be respectively actuated and deactuated whenever the platform is on the positive side of the midpoint of its travel. When the platform **35** is centered within its X axis range of movement, both switches LSX1 and LSX2 will be actuated.

Two limit switches LS1 and LSC aid in the control of the cross slide movement. The first switch LS1 is associated with a yieldable feeler **76** which normally projects about one-quarter of an inch beyond the adjacent front surface of the wheel **21** and which will engage and be deflected by the roll surface as the cross slide **40** moves the wheel **21** inwardly toward the roll. Such deflection of the feeler **76** actuates the limit switch LS1, and the contacts of the latter control the motor MC in a manner which will be described later. The switch LS1 and the feeler **76** are shown only diagrammatically in FIG. **6A**, and these parts may form the components of a sensing mechanism of the type disclosed in more detail by Klein U.S. Pat. No. 3,494,079. Reference may be made to such patent if greater detail is desired.

The second switch LSC serves to signal when the cross slide **40** has been retracted to the outward limit of its travel. As here shown in FIG. **6A**, the limit switch LSC is disposed in a position such that its actuating finger will be engaged and deflected by a small projection **78** on the cross slide **40** when the latter has been moved outwardly to a fully retracted position.

4. Probe Assemblies

In the practice of the invention it is desirable to sense the location of the roll surface at any point along its length, and to signal the displacement of that surface from some reference line which is parallel to the Z axis of wheel movement. For this purpose, a rear probe assembly **80** is supported for movement in unison with the wheel **21** along the X axis, and is located such that its probe **81** may engage the surface of the roll **22** at a point which is diametrically opposite from the point at which the wheel **21** engages the roll surface during grinding operations. More specifically, the probe assembly **80** is supported on the rear extremity of a cantilever arm **82** (FIG. **2**) extending from a pedestal **84** fixed to the main carriage **42** at a location leftward of the wheel **21**, and angled or offset as viewed from above (FIG. **1**) so that the assembly **80** is directly opposite the wheel.

The arm **82** may be swung upwardly about a pivot **85** (FIG. **2**) to permit insertion or removal of a roll into or from the steadyrests. With the arm in position and the probe assembly **80** located as shown, it will be apparent that as the wheel **21** is moved lengthwise of the roll on the Z axis along what may be termed an element of the roll surface, the probe **81** moves with the wheel and and may be advanced into engagement at any point along what may be termed an element which is diametrically opposed to or located 180° from the lime or element which the wheel engages.

Referring to FIG. **4**, the rear probe assembly includes a movable gage body **88** longitudinally slidable within a housing **89** toward or away from the roll surface in response to forward or reverse stepping of a step motor MRG which drives a lead screw **90**. A nut **91** fixed to the body **88** is engaged with the lead screw. A feedback pulse generator P*r* is also driven by the lead screw **90** and produces signals which indicate the displacement of the gage body **88** as it moves within the housing **89**. When the body is fully retracted into the housing, the nut engages the feeler of a limit switch LSRG and thus actuates the latter.

The probe **81** is formed as a rod slidable lengthwise within the body **88**, being normally urged outwardly by a compression spring **92** but retracted against the bias of the spring upon energization of a solenoid RS which thereupon attracts an armature **94** fixed to the probe. When the probe is released by deenergization of the solenoid RS, and the body **88** is moved toward the roll **22**, the tip of the probe **81** will engage the surface of the roll and thus shift the probe relative to the body **88**. The position of the probe relative to the body **88** is signaled by an appropriate transducer, here shown as a linear variable differential transformer (LVDT) **95** whose core **96** is formed on and movable with the probe. Such transformers are per se well known and, as shown in FIG. **12**, comprise a primary winding **98** excited from a suitable ac. voltage source **100** and induc-

tively coupled to two opposed, series connected secondary windings **101, 102**. When the core is centered within the annular assembly of the three windings, the voltages induced in the two secondary windings cancel, and the output voltage *Vo* is substantially zero or has what is called a null value. As the core **96** moves to the left or right (FIG. **12**), however, the output voltage *Vo* increases proportionally in amplitude with the displacement of the core from a center or null position, and the output voltage is respectively in phase or out of phase with the exciting ac. voltage applied from the source **100** to the primary winding **98**. Thus, the voltage *Vo* is proportional in amplitude to the displacement of the core **96** from a centered position relative to the windings of the transformer **95**, and is agreeable in phase polarity with the sense of such displacement. The voltage *Vo* is preferably applied to an AC/DC converter **104** which also receives the exciting voltage from the source **100**. The converter **104** produces a DC output voltage proportional in magnitude to, and in agreement in polarity with the sense of, the displacement of the core **96** from a centered position. This latter voltage after passage through am amplifier **105** is here labeled E, and the manner in which it is used will be described below. It will be assumed that as the probe **81** and thus the core **96** move inwardly or outwardly relative to the body **88** (FIG. **5**) from a null position, the voltage E takes on a positive or a negative polarity, respectively.

A front probe assembly **106** adapted to sense the location of the surface at the front side of the roll **22** is mounted on the main carriage **42** so that it moves back and forth along the Z axis in unison with the wheel **21**. This front probe assembly cannot, however, be aligned directly with the center of the wheel face (as is the rear assembly **80**), and thus it is offset therefrom a predetermined distance, i.e., 30.0 inch, as shown in FIG. **6A**. The front probe assembly **106** is substantially identical to the rear probe assembly **80** (see FIG. **4**), and includes a housing **108** mounting a stepping motor MFG connected to a lead screw **109** for driving a probe body **110** toward or away from the front surface of the roll **22**. Rotation of the lead screw **109**, and thus motion of the probe body **110** is signaled by a feedback pulse generator Pf, and a limit switch LSFG is actuated when the body is fully retracted. The probe body contains a spring **111** and solenoid FS energizable to retract the front probe **112** against the bias of the spring; there being a transducer in the form of an LVDT **114** for signaling the position of the probe **112** relative to a centered or "null" position relative to the body **110**. As shown in FIG. **13**, the primary winding of the LVDT is excited from the ac. voltage source **100**, and the output signal from the secondary windings is passed to an AC/DC converter **115** whose output signal is amplified by an amplifier **116** to create a DC output voltage *Ef* which is proportional in magnitude to, and agreeable in polarity with, the extent and sense of the displacement of the probe **112** from a centered or "null" position. It may be noted here that the voltage *Ef* is applied to a voltmeter **118** which gives a direct visual indication of the polarity and magnitude of that voltage. The voltmeter may be calibrated, for example, in ten thousandths of an inch. That same voltage *Ef* is supplied as an input to zero or null detecting circuit **119** which may take any of a variety of forms well known to those skilled in the art and which produces a predetermined output voltage only when the voltage *Ef* is substantially zero. The output of the zero detector **119** is connected to the coil of a relay RZF, and the latter relay will thus be energized only when the voltage *Ef* is substantially zero and thus when the probe **112** is at a centered or null position relative to its body **110**.

5. Proximity Switches

To assist in finding a reference point on the workpiece, one or more workpiece sensors are mounted for movement with the main carriage **42**. To locate these sensors substantially in alignment with the wheel **21**, they are preferably disposed on that end of the rear probe body which is closest to the roll surface. In the present instance and as shown in FIGS. **4** and **5**, two proximity switches PSR and PSL are carried on the innermost end of the probe body **88**, being spaced on the right and left sides of the probe **81** by predetermined equal distances S. When the probe body is extended out of the housing **89** to a position at which the probe **81** engages the roll surface and shifts the core **96** to a null position, then the proximity switches will be disposed within less than one-quarter inch from the roll surface. By magnetic or other appropriate sensing action, the two switches PSR and PSL will be actuated so long as they are opposite the surface of the metal roll. Of course, if the carriage is moved axially to a position at which either of these switches is beyond the left or right edge of the roll, that particular switch will be deactuated.

C. The Control System in General

In the practice of the present invention, two separate, previously prepared "programs" are stored and used to control the operations of the grinding machine **20**. The first program is formed by successive blocks of numerical data which define the successive increments of multi-axis motion making up a contoured path which the wheel must follow in shaping the workpiece with the desired concave or convex profile. The successive data blocks or instructions of the first program may take the form of conventional and well known three axis numerical contouring commands, each instruction containing a numerical designation of the incremental movement to be executed by the wheel **21** along the Z, B and X axis in moving from one point to another along the contour.

The second stored program is formed by successive blocks of numerical data which define successive commands representing different ones of a plurality of ancillary routines or operations to be carried out successively in the treatment of a given roll. The commands, which are read successively from storage and executed in sequence, fall into two catagories. Commands of the first category define any of several auxiliary functions and are executed by a change in the condition or position of one or more of the motors or instrumentalities on the grinding machine. The second category of command calls for utilization of all or a part of the data in the first stored program, so that such second type of command is executed by reading out and using some or all of the blocks or instructions of the first program to make the wheel **21** move wholly or partly along the contoured path which is represented by the first program. By this procedure of storing first and second programs and causing the latter to initiate the use of the former, the same profile data contained in one first program may be employed for the grinding of a plurality of rolls which are to be given the same surface profile but which are not otherwise identical in diameter, length, degree of wear or material. A second type of program may be prepared for each individual roll so as to accommodate for differences of the type noted.

1. Contouring Apparatus

As shown in FIG. **6B**, the first program or set of profile instructions is stored on a first digital record, here illustrated as an endless punched tape **121** threaded in a tape reader **122** and otherwise disposed in a tumble box **124**. The tape **121** is made in the conventional and well known fashion, each "block" thereof representing the Z, B and X axis components (any of which may be zero) which make up one increment along the desired contour path. Because such contouring control punched tapes are familiar to those skilled in the art the tape **121** need not be illustrated in detail. By way of example, the tape **121** may be prepared according to E.I.A. code specifications, with each block beginning with a block number designation, then containing the Z, B and X axis component numbers, and ending with an "end of block" or **EOB** code.

When the tape reader **122** is started by a "start" signal, the successive sets of output signals resulting in the reader **122** from the reading of successive rows of punched holes, are supplied to a multi-axis contouring director **125**. Since such directors are well known to those skilled in the art, the details

of the rather complex director will, for the sake of brevity, not be described here. For such details, reference may be made to any of U.S. Pat. Nos. 3,002,315; 3,069,608; 3,173,001; 3,390,315 or to the literature published by manufacturers of numerical contouring systems. It will be noted only briefly that the director **125** contains decoding circuits to accept the output signals from the tape reader **122**, and responds to each E0B signal read from the tape **122** by sending a "stop" signal back to the reader **122**. Thus, the successive blocks of the tape **121** are read individually in sequence as the contouring director causes the wheel **21** to execute the motions which those blocks call for. Each block of data causes the director to produce command signals which vary all in the same period of time by amounts and in senses which correspond to the Z, B and X axis component displacements represented by that block. The actual displacements of the wheel **21** are signaled by pulses from the generators P*z*, P*b* and P*x* fed back to the director terminals labeled B*f*, X*f*, Z*f* in FIG. 6B. Servo comparing means in or associated with the director **125** produce DC error voltages which in polarity and magnitude represent the instantaneous difference between the actual displacements and the displacements represented by the command signals for the three respective axes. Such error voltages appear on the terminals labeled Z, B and X in the director, and are passed via suitable amplifiers or motor controllers **126**, **127**, **128** to the motors MZ, MB and MX. In this way, the motors are energized to move the wheel **21** along the Z, B and X axes to produce the commanded increments of motion along the path.

When the instruction from one block on the tape **121** has been executed, the director **125** normally produces a signal on its "start" output line, such signal starting the tape reader **122** so that the next block or instruction is read into the director. Buffer storage in the director permits quick transition from one block of data to the next, so that the successive increments of the path represented by successive instructions on the tape **121** are executed substantially as one continuous motion, and the wheel is moved along the desired profile path such as the convex path **130** illustrated to an exaggerated degree in FIG. **9**.

The shape of such contour may be different for different sets of rolls, and indeed may be concave or undulating in some cases. For each different contour, a separate program of profile instructions is stored, for example, on a different punched tape **121**. Once any given profile program is stored, it may be called out and used repeatedly to execute repeated passes of the cutting tool or wheel **21**. The same path may thus be followed as many times as desired; with inward offsets or increments, to perform rough grinding, finish grinding, or polishing operations. Moreover, in many cases, a plurality of rolls in a set for a given rolling mill are all to be crowned with the same contour, even though the length of the individual rolls may differ. In these instances, the same program of profile instructions is usable in the grinding of each of the plurality of rolls, despite the fact that the individual rolls may be worn to varying degrees of surface irregularity. It is possible in the practice of the present invention, therefore, to compile a library of programs stored on digital media, such as a plurality of the punched tapes **121**, defining a relatively small plurality of profiles which will be needed on various types and sizes of cylindrical workpieces or rolls. Despite the individual differences in surface irregularities, lengths, materials and the like possessed by different rolls, the same profile program and profile punched tape may be utilized to effect the machining of different rolls which are to have the same finished contour.

Although the profile or path may be of any desired shape, and differ on the left and right halves of the roll, the roll in most cases is to be finished with its surface symmetrical about the lengthwise center LC (FIG. **9**) between the right and left edges. That is, as the wheel **21** is moved through equal displacements $+\Delta Z$ and $-\Delta Z$ from the roll center LC, the total inward motion $-\Delta X$ of the wheel will be the same, and obviously the extent of swiveling $+\Delta B$ and $-\Delta B$ will be equal but opposite in sign. The roll center LC is thus usually a reference point of symmetry for the contouring motion to be imparted to the wheel.

When the profile is symmetrical, the program of data on the contouring punched tape may contain groups of blocks which are identical in a numerical sense but differ only in the signs of the Z, B and X component distances to be moved in effecting the small successive increments of multi-axis motion.

As illustrated in FIG. **9**, to move the wheel along the three axes so that it follows the contour **130** for the right half of a roll **22**, the profile tape **121** may contain a first set of instruction blocks **N001** to **N100** which define the profile over a distance greater than one-half the length of the roll, i.e., greater that ½L. The sense of the Z, X and B axis movements are positive, negative and positive, respectively. The blocks **N001** to **N090** are sufficient to move the wheel **21** to the right, i.e., positively, along the Z axis by a total distance of ½L for the particular roll here shown with coordinated negative X axis motion and positive B axis motion. Thus, in the reading of the punched tape **121**, the blocks **N091** to **N100** thereon can simply be skipped over or ignored since the particular roll **22** here involved is shorter in length than the maximum length for which the profile program has been prepared.

The blocks **N111** to **N200** contain numerical commands to move the wheel **21** along the profile path from the right back to the center LC, and the numerical data in these blocks may be the same as in blocks **N100** to **N001**, respectively, except that the signs of the axis displacements are reversed. That is, the Z motion is negative, the X motion is positive, and the B motion is negative. If the initial movement under control of blocks **N001** to **N090** stops the wheel at the right end of the roll, then blocks **N101** to **N110** will be skipped or ignored, and the instructions of blocks **N111** to **N200** will be followed to bring the wheel back to the center LC.

In like manner, blocks **N201** to **N300** may be followed to move the wheel from the center LC along the profile toward the left. These blocks contain the same numerical data as blocks **N001** to **N100**, respectively, except that the signs of the Z, X and B axis motions are all negative. If the wheel reaches a Z axis displacement of ½L at the end of block **N290** (as here shown), then blocks **N291** to **N300** may be skipped or ignored.

To return the wheel from the left by motion in a rightward direction to the roll center LC, blocks **N301** to **N400** contain numerical data identical to that of blocks **N300** to **N201** (or **N100** to **N001**),,respectively, but the signs of the Z, X and B axis motions are all positive. If the wheel has been stopped at the left edge of a roll corresponding to the left position reached at the end of the block **N290**, then rightward movement of the wheel is produced by a skipping and ignoring of blocks **N301** to **N310**, so that the wheel follows the instructions of blocks **N311** to **N400** in returning to the center LC.

The foregoing will be fully understandable to those familiar with the art of numerical contouring, and it will be appreciated that in actual practice only one set of blocks (say, blocks **N001** to **N100**) need be digitally stored or contained on the punched tape **121**. If this is done, controls are provided so that such blocks are repeatedly read forwardly and reversely by the reader **122** to supply contouring instruction signals to the director **125**, with the latter containing devices to reverse the signs of commanded axis displacements when the wheel **21** is to be moved in a right or left direction across either the right or left half of the roll **22**. The single stored contouring program is relatively short and simple, and it may be used repeatedly to execute successive, offset motions along the desired path, as described below. The same stored profile data may also be used for any of several rolls which differ individually in their axial length, but which are to have the same finished profile.

2. Sequence Command System

The second stored program is here termed a program of sequence commands, and such commands are stored in digital form so as to be called out and executed successively. In the present embodiment, sequence commands are stored in the successive blocks of a punched tape **130**, hereafter called the sequence tape, which is threaded for passage through a sequence tape reader **131** between supply and take up reels. Each block on this tape may begin with rows of punched holes representing a block number, followed by successive sets of rows which represent address codes and number commands, and with each block ending in the familiar "end of block" code E0B. The tape reader **130** is initially started by momentary closure of a manual start switch **132**, and is thereafter restarted by application of a momentary signal or positive-going voltage transition to its input terminal *g*. As the reading of each block of the tape **130** is completed, the E0B output signal is recognized in decoding circuits **134** and fed back to a "stop" terminal, thereby interrupting the transport and reading of the tape until the terminal *g* is next energized.

The trunk of output lines of the tape reader **131** leads to the decoding circuits **134** which receive the output signals representing the various address codes and which route the numerical data following each such address code into corresponding storage devices or registers. Each of these storage devices holds the numerical data placed therein until a new set of numerical data is supplied thereto, and signals in digital form (for example, in binary coded decimal notation) on its output trunk the stored numerical value. For the exemplary embodiment here described, the sequence tape **130** may contain addressed commands representing a Z axis displacement, an X axis displacement, a feed rate F, a roll speed S, a wheel speed W, a C axis rate of infeed, a time delay duration P, a probe displacement U, and a diameter D, — and the number representing such commands read from the tape are routed by the decoding circuits **134** for storage in the respective digital storages **140–148**. Other addressed commands may also appear on the punched tape **130**, such for example, as M codes and G codes to be described below. As each such M code or G code is read from the punched tape **130** and represented by output signals from the tape reader **131**, the decoder circuits **134** cause the correspondingly labeled output terminal to be momentarily energized, i.e., to receive a momentary voltage. For example, if the code M02 is read from any block of the punched tape **130**, then the terminal labeled M02 in FIG. **6B** will receive a momentary voltage thereon. The manner in which these M and G code signals are utilized will become clear as the description of the invention proceeds.

The signals representing Z, X and F commands are routed from the storage devices **140–142** to the contouring director **125**. The Z and X commands cause the director to move the wheel **21** through the numerically designated distances along the Z or X axes, as hereafter discussed. The F command signals from the storage device **142** control the director **125** such that movement of the wheel **21** along the profile occurs at the designated velocity or feed rate. Velocity or feed rate control in a contouring director is well known to those skilled in the art, and it need not be treated in further detail.

The signals from the storage devices **143–145** are supplied to digital-to-analog converters **153–155** respectively which serve to convert the signaled numerical values into proportional analog signals, here assumed to be dc. voltages Vs, Vw and Vc. By way of example, if the stored S command is S24, thereby calling for a roll speed of 24 r.p.m., the DC voltage Vs is proportional to the number 24 and is supplied through a suitable amplifier or motor controller **156** (and relay contacts RM04b when closed) to excite the motor MH such that it drives the roll 22 at the desired speed of 24 r.p.m. In like manner, the voltage Vw is supplied as an input to a suitable controller or amplifier **158** and thence through contacts RM17b (when closed) to the wheel motor MW so that the wheel **21** is driven by that motor at a speed corresponding to the value represented by the command number held in the storage device **144**. The output signal from the tachometer **38** may be applied as a negative feedback signal to the amplifier **158** so that the speed of the wheel motor MW is more precisely controlled.

For the purpose of providing a signal which is representative of the torque load on the wheel motor MW (and which thus indicates whether or not the wheel **21** is in grinding engagement with the roll **22**), a resistor **159** is connected in series with the wheel motor MW, and the voltage across this current-sensing resistor will therefore be generally proportional to the load on the motor. A potentiometer **160** may be connected across the current-sensing resistor **159** to derive on its wiper **160***a* a voltage which is a predetermined fraction of that appearing across the sensing resistor **159**. The voltage between the lower end of the potentiometer **160** and the wiper **160***a* is supplied to the coil of a sensitive relay CS, and the latter will thus be energized whenever the wheel **21** is in grinding engagement with the roll **22**, i.e., when a torque load is imposed upon the motor MW so that it draws more than normal, no-load current.

The voltage Vc from the digital-to-analog converter **155** is supplied to a summing device here shown diagramatically as an amplifier **161**. A second input voltage to this amplifier is supplied (when the contacts RM74*c* are closed) from the wiper **162***a* of a potentiometer **162**. The latter is excited with the same voltage which is fed to the relay coil CS, and thus the second input signal to the amplifier **161** is proportional to the torque load imposed on the grinding wheel and thus on the motor MW. The output voltage Ec from the amplifier **161** is thus proportional to the algebraic difference between the voltage Vc and the torque load imposed on the wheel **21** by virtue of its engagement with the roll **22**. This output voltage Ec is utilized to control the continuous infeed of the wheel, as more fully described below.

3. Data Manipulation Apparatus

Signals representing various numbers are manipulated in the control system to derive the results of arithmetic operations, and this will be made clear as the operational description is detailed below. Before such detailed description is set out, however, it will be helpful to note briefly the components of the data manipulation apparatus here shown by way of example. Referring to FIG. **10**, the exemplary embodiment of the control apparatus includes means for performing certain arithmetic operations on digitally signaled numbers. For this purpose, a computer **165** is shown in block form as having an input bus IB and an output bus OB, each made up of multiple conductors upon which multi-digit decimal numbers may be signaled in binary coded decimal notation. Such computers may take a variety of forms; they are well known per se and available commercially. It will suffice to observe simply that if two numbers are represented by successive signals on the input bus IB, the computer will signal the sum or difference thereof if a function signal is applied to the "add" or "subtract" control terminals *r* or *t*, respectively. On the other hand, if a function signal is applied to the control terminal *v*, the computer will divide by 2 the number then stored therein and represented on its output bus OB, i.e., will then signal on the output bus OB one-half of the first number.

Signals representing several different numbers may be applied selectively to the input bus IB. The number contained in and signaled by a Z axis bidirectional counter **166** may thus be fed to the input of the computer **165** by application of a control signal at *a* to open readout gates **168** having their inputs connected to the output conductors of that counter. Also, by application of control signals *u* or *w*, readout gates **169** or **169***a* may be respectively opened to place the number held in the D storage device **148** or the U storage device **147** (FIG. **6B**) on the input bus IB. Similarly, the numbers signaled by front or rear probe bidirectional counters **170** or **171** (FIG. **11**) may be fed into the computer **165** by opening readout

gates 172 or 173 in response to enabling signals at control terminals *o* or *o*1, respectively.

The result of any computation in the computer 165 may be transferred to various places for storage and use. For example, by the application of an enabling signal at *b* (FIG. 10) the signaled output of the computer may be transferred through gates 174 to preset the bidirectional counter 166. By the application of an enabling signal *s* to a readout device 175 (FIG. 10), the latter will be actuated to print out or display the number then signaled on the computer output bus OB. Finally, the application of an enabling signal at *z* to preset gates 176 (FIG. 11) will open the latter to preset the bidirectional counter 170 so that it initially stores and signals the number then represented on the output bus OB.

The Z axis counter 166 in FIG. 10 is coupled to respond to motion along the Z axis by counting the pulses produced in the pulse generator Pz. The "two phase" signals from that generator are supplied to a direction sensor and pulser 178 which produces one pulse on an output line 179 for each unit distance (say 0.0001 inch) which the main carriage 42 moves in a positive (right) direction, and which produces one pulse on an output line 180 for each unit distance which that carriage moves in a negative (left) direction. The counter 166 thus normally signals a number which represents the algebraic sum of all of the movements represented by pulses fed thereto, and its output conductors thus may represent in BCD notation the position of the main carriage 42 and thus the Z axis position of the wheel 21. The counter 166 may form a part of the director 125 where it serves the normal function of signaling distances moved along the Z axis during the execution of contouring motions; but this counter may if desired by provided as a separate counter apart from the regular three axis contouring director in order to serve the purposes which will be made clear below.

The front and rear probe bidirectional counters 170 and 171 (FIG. 11) receive the output pulses from direction sensors and pulsers 184 and 185 which are respectively coupled to the pulse generators Pr and P*f* in the front and rear probe assemblies 80 and 106. When the step motor MRG for the rear probe is energized to drive the probe body 88 (FIG. 4) outwardly or inwardly relative to roll 22, then pulses appear on the "out" or "in" terminals of the direction sensor and pulser 184 (FIG. 11) so that the counter 170 counts up or down. In this way, the algebraic sum of the distances moved by the probe body 88 is registered in the bidirectional counter 170, and if that counter is preset to zero when the probe body is at a null or reference position, then its displacement from that reference position will be signaled in digital form on the output conductors of the counter. The bidirectional counter 171 is associated with the front probe assembly and the front probe pulse generator P*f* functions in the same manner.

As noted above, the rear probe counter 170 may be preset by the application of an enabling signal at *z* to a first set of presetting gates 176. This same counter may also be preset to either of the two other digitally signaled numbers. When an enabling signal is applied at *y* to open presetting gates 186, then the counter 170 will be preset to contain the number then digitally signaled on the output conductors of the U storage device 147 (FIG. 6B). Alternatively, the application of an enabling signal at *p* to a set of presetting gates 188 opens the latter to transfer signals representing a predetermined distance, here 33'', from a digital signaling source 189, so as to preset the number 33.0000 into the bidirectional counter 170. The bidirectional counter 171 associated with the front probe assembly may be preset to contain the same predetermined number, i.e., 33.0000 inch by application of an enabling signal to a control terminal *q* of presetting gates 190 which have their inputs connected to a signaling source 189*a*.

D. Methods and Apparatus for Grinding a Roll

With the foregoing introduction to the locations and interconnections of some of the elements located on the machine tool or included in the control apparatus, a more detailed description of the methods and apparatus may now proceed. Such description may be presented most expeditiously as a narrative of the operational steps which occur successively, and with the control circuitry of FIGS. 15A–G being described as appropriate when successive ones of the steps are taken up.

1. Setup Procedure

With the rear probe-supporting arm 82 swung upwardly about its pivot 85 (FIG. 2), a new roll to be finished, or an old and worn roll to be reground, is placed in the grinding machine 20 with its right and left necks respectively supported by the right and left steadyrests 28 and 29 (FIGS. 1 and 6A). The clamp or collar 31 is fixed to the right neck so that the headstock is drivingly coupled to the roll 22. At this time, the lengthwise axis of the roll 22 may be grossly misaligned from parallelism to the Z axis of the machine, and it is desirable to roughly approximate such alignment by a manual setup procedure.

As a first step, the control circuits of FIGS. 15A–G are enabled by connecting the voltage supply lines therefor to suitable voltage sources. As shown in FIG. 15A, a positive voltage source here represented by a battery 200 and a negative voltage source here represented by a battery 201 are connected between a line L2, shown as grounded or at zero volts potential, and positive and negative voltage supply lines L1 and L3 through normally open contacts R1*c* and R1*b* of a relay R1. The operator need only momentarily close a start switch ST to energize the relay R1 which then seals in through its normally open contacts R1*a*, normally closed contacts RM02*e*, and a normally closed stop switch SP. With this, the contacts R1*c* and R1*b* are closed to connect a positive supply voltage to the line L1 and a negative supply voltage to the line L3. Throughout the description which follows, it may be understood that the lines L1 and L3 reside at positive and negative voltages relative to the line L2 in FIGS. 15A–G.

The appearance of a positive voltage on the line L1 will normally energize the solenoids RS and FS (FIG. 15C) thereby retracting the front and rear probes 81 and 112 into their corresponding probe bodies 88 and 110 (FIG. 4). The main carriage 42 is then moved under manual control to a position such that the front probe 112 is near the left end of the roll 22. The operator accomplishes this by closing a manual push-button switch S2 (FIG. 15A) which connects a potentiometer PT1 between the supply lines L3 and L2, creating a negative voltage on the wiper PT1*a*. The latter wiper is connected to one input of the amplifier or motor controller 126 previously shown in FIG. 6B, and the negative input voltage applied to that amplifier results in a corresponding negative excitation voltage being applied to the carriage motor MZ. Accordingly, the motor MZ drives the carriage until the front probe assembly 106 is located near the left end of the roll 22, and the operator terminates such movement by releasing the switch S2.

Thereafter, the operator opens a manually controlled, normal closed switch S3 (FIG. 15C) to deenergize the solenoids FS and RS. The front probe 112 is biased toward the adjacent roll surface by its spring 111. The operator may now move the probe body 110 inwardly toward the roll 22 by closing a manual push-button switch S4 which supplies a positive voltage to a step pulse driver 204, causing the latter to supply pulses to the stepping motor MFG so that the lead screw moves the body 110 (FIG. 4) toward the roll surface. When the probe engages the roll surface and is deflected into the probe body, the operator may observe the voltmeter 118 (FIG. 13) to read the magnitude of the signal Ef produced by the front LVDT 114. The operator may then release the switch S4 to stop the step motor MFG when that voltmeter reading has any particular value, say, 0.004 inch. This establishes a reference reading for the front probe assembly at the front side of the left end of the roll 22.

The operator then recloses the switch S3 to energize the solenoids RS and FS, thereby retracting the front and rear probes into their respective bodies. Next, the operator may

close a manual push-button switch S1 (FIG. 15A) to connect a potentiometer PT2 between the lines L1 and L2, thereby creating a positive voltage on the potentiometer wiper PT2*a*. This supplies a relatively large positive voltage to the positive input terminal of the amplifier or controller **126**, and the latter therefore supplies a positive voltage to the motor MZ, so that the carriage **42** is driven to the right or in a positive direction along the Z axis. When the carriage **42** has been moved to locate the front probe assembly **106** at some point generally near the right end of the roll **22**, the operator releases the switch S1. Next, the operator opens the switch S3 to deenergize the solenoids RS and FS, thereby releasing the front and rear probes for engagement with the surface of the roll **22**. The operator may now observe the reading on the voltmeter **118** to determine if it is reasonably close to the reading previously obtained with the front probe assembly at the left end of the roll. In the event that the present reading of the voltmeter **118** indicates a discrepancy of more than, say, 0.002 inch, the operator may close either of the push-button switches S6 or S7 (FIG. 12) so as to connect a positive or a negative voltage source (here shown by way of example as batteries **205, 206**) to the steadyrest motor MS, so that the right steadyrest is moved outwardly or inwardly and shifts the right end of the roll **22** by swinging it about its pint of support in the left steadyrest. As such movement of the right end of the roll occurs, the front probe **112** will be shifted inwardly or outwardly relative to its probe body, and the front probe signal Ef (FIG. 13) will correspondingly change. When the operator observes that the reading of the voltmeter falls within +0.006 and +0.002, he knows that the front surface of the roll at its right end is within ±0.002 inch of a line drawn parallel to the Z axis from the front surface of the roll at the left end. The operator then releases the switch S6 or S7 in FIG. 12, and is assured that the roll **22** has been located in the machine with its front surface roughly aligned parallel to the Z axis.

This is only a preliminary and rough alignment, since worn spots or surface irregularities on the roll will result in errors in this manual alignment procedure. Nevertheless, after such rough alignment procedure, it is known that when the wheel **21** is brought to the same inward position along the X axis at opposite ends of the roll, it will engage the roll surface at both ends to grind small amounts of material therefrom. This makes certain that the grinding of gaging bands as hereinafter described results in the removal of some material at each end of the roll.

Following the rough alignment procedure, the operator recloses the switch S3 (FIG. 15C) so that the solenoids RS and FS are again energized and the probes are retracted. The operator may now momentarily close a push-button switch S5 to energize the step pulse driver **204** such that the step motor MFG for the front probe assembly retracts the body **110** into the housing **108** (FIG. 4).

As the next step in the initial setup procedure, the operator causes all of the storage registers and counters (FIGS. 6B, **10** and **11**) to be reset to zero. This is done by conventional means (not shown) which may include a manually operated reset switch which is momentarily closed.

Next, the operator places the profile tape **121** which numerically defines the profile to be given to the roll **22** in the tape reader **122** (FIG. 6B), and he similarly places the sequence tape **130** in the tape reader **131**, so that the tapes are ready to be read and utilized in controlling the operations of the grinding machine. At this time, the operator may also feed into the system a fractional constant by setting a dial **208** (FIG. 12) which correspondingly adjusts the wiper **209***a* of a potentiometer **209**. The nature of this potentiometer setting and its purpose will be described in more detail below. All is now in readiness for automatic operation of the control system and grinding machine to grind the roll **22** to a desired surface contour and finish. This automatic operation is commenced by the operator momentarily closing the push-button switch **132** (FIG. 6B) so as to start the tape reader **131** and cause reading of the first block of command data contained on the sequence tape **130**.

2. Location of Lengthwise Center; M61

As noted above, the profile program stored on the profile tape **121** is made in the first instance with the center of the roll as an assumed zero or reference point, so that the profile is symmetrical about the roll center. To advantage, the roll **22** need not be carefully placed or adjusted lengthwise on the steadyrests **28, 29** to locate the lengthwise center of the roll precisely relative to the machine base. Indeed, the length of the roll need not be precisely known. On the contrary, in the practice of the invention, the lengthwise center of the roll is located after the latter is in the machine, and the control system is caused to use that location as a zero or reference point for grinding the roll with the desired, programmed profile.

The first block of the sequence tape **130** will in most instances contain simply:

N01
M61
E0B

Reading of the block number code N01 produces no responsive operation. The M61 code calls for execution of a "center finding and zero referencing" routine. Thus, when the operator starts the system by momentary closure of the switch **132** (FIG. 6C), the reader **131** will read and signal codes N01, M61, E0B, and then stop.

The momentary appearance of a voltage on the M61 terminal of the decoder circuitry **134**, and upon the same terminal in FIG. 15A, results in pickup of a relay RM61 which then seals in through its own contacts RM61a and normally closed contacts R7a. As a result, contacts RM61*b* and RM61*c* close to supply the positive and negative voltages from lines L1 and L2 to auxiliary voltage supply lines labeled 61+ and 61−. These auxiliary voltage supply lines are thus effective during the execution of a center finding and reference setting routine. As a consequence of the supply voltages appearing on line 61+ and 61−, as well as the energization of the relay RM61, several operational functions are produced, and these will be briefly and individually treated.

a. Movement of the Swivel Base

to the Center of B Axis Travel

If the swivel base **41** is disposed in a negative or a positive direction from its center of B axis travel, then the limit switch LSB2 of LSB1 (FIG. 6A) will be actuated. Thus, the normally closed limit switch contacts LSB1*a* or LSB2*a* in FIG. 15A will be respectively closed to connect a potentiometer PT3 or a potentiometer PT4 such that it is excited with a positive or negative voltage from the line 61+ or 61−. Accordingly, the wiper PT3*a* or PT4*a* will supply a positive or negative potential to an input of the amplifier or motor controller **128** associated with the B axis motor MB, causing the latter to be energized for rotation in a positive or negative direction so as to move the swivel base **41** back toward its centered position. When the centered position is reached, the switches LSB1 and LSB2 will both be actuated, and the contacts LSB1*a* and LSB2*a* will both be open, so that the previously excited one of the potentiometers PT3 or PT4 is deenergized to remove the input voltage from the amplifier **128**. Accordingly, the motor MB is stopped with the swivel base **41** located at the midpoint in its range of B axis travel. Thus, in response to the reading of an M61 code from the sequence tape, the swivel base will be set to a centered position.

It may be noted briefly that the amplifier or motor controller **128** which appears in FIG. 15A is also shown in FIG. 6B. This amplifier receives the error signal from the terminal *b* of the contouring director **125**, and thus during contouring operations serves to energize the motor MB to cause coordinated movement of the wheel **21** along the B axis. The potentiometers PT3 and PT4 serve as auxiliary inputs for energizing the motor MB when the swivel base is to be set to its centered position under the control of the limit switches LSB1 and LSB2.

b. Setting the Platform 35

to the Center of X Axis Travel

As shown in FIG. 15A, normally closed limit switch contacts LSX1a are connected in series with a potentiometer PT7 between the line 61+ and the line L2; and normally closed limit switch contacts LSX2a are connected in series with a potentiometer PT8 between lines 61− and L2. The potentiometer wipers PT7*a* and PT8*a* are connected to positive and negative inputs of the operational amplifier or motor controller 127 associated with the motor MX. Thus, when the lines 61+ and 61− are active, the contacts LSX1*a* will be closed to excite the potentiometer PT7 if the platform 35 is on the negative side of its center position and the switch LSX1 is deactuated. Alternatively, the switch LSX2 will be deactuated and its contacts LSX2*a* closed, if the platform 35 resides on the positive side of its center of travel. The motor MX will be energized to turn in one direction or the other so as to bring the platform 35 and the wheel 21 to the center of the X axis range of motion, whereupon both switches LSX1 and LSX2 will be simultaneously actuated so that both contacts LSX1*a* and LSX2*a* will be open to deenergize the motor MX. Thus, in response to the reading of an M61 code, the movable element or tool here represented by the wheel 21 is automatically moved under the control of limit switches LSX1 and LSX2 to the center of the X axis range. It may be noted briefly that the operational amplifier 127 also receives the error signal from the X output terminal of the director 125 (FIG. 6B) so that during normal contouring operations, the motor MX is controlled for coordinated contouring movement in the normal fashion.

c. Movement of Proximity Switches

to Operative Positions

As a prelude to moving the carriage 42 to a Z axis position such that the wheel 21 is at the lengthwise center of the roll, it is necessary to extend the rear probe body 88 so that the proximity switches PSR and PSL (FIGS. 4 and 5) thereon are close to the roll surface. To do this, an M86 routine is executed as a part of the overall M61 routine.

M86 Routine. The input terminal labeled M61 in FIG. 15B is momentarily energized when the M61 code is read, and this picks up a relay RM86 which seals in through its own contacts RM86a and normally closed relay contacts RZ*b*. The latter are controlled by a relay RZ (FIG. 12) connected to the output of a zero detector circuit 210 which produces an output voltage only when the voltage E is substantially zero, and thus only when the rear probe 81 holds the core of the LVDT 95 in a centered or null position. The M86 code calls for release of the rear probe and driving of the probe body 88 (FIG. 4) until the signal E is reduced to zero. This comes about because pickup of relay RM86 (1) closes contacts RM86*b*, so that a relay RM84 (FIG. 15C) is energized and sealed in via contacts RM84*a*, RM85*b* and its normally closed contacts RM84*b* open to deenergize solenoids RS and FS, thereby releasing the front and rear probes 81 and 112 so that they are extended under the influence of their biasing springs; and (2) closes contacts RM86*c* (FIG. 15B) so that a positive voltage is applied to a stepping pulse driver 211 which in turn pulses the motor MRG in a direction to move the probe body 88 toward the roll. In consequence of such movement of the probe body 88, the probe 81 will engage the roll surface and be shifted inwardly relative to the body. When the core of the LVDT 95 reaches a null position, the voltage E (FIG. 12) will go to zero, and the zero detector 210 will energize the relay RZ, thereby opening the contacts RZb (FIG. 15) to drop out the relay RM86. Therefore, the contacts RM86c open to terminate stepping by the motor MRG, and the probe body 88 is halted in a position such that the probe 81 is deflected to produce a null or a zero output signal from the LVDT 95.

This completes the execution of the M86 routine, since the probe body has been brought to a position at which the signal E from the rear probe assembly is nulled. The relay RM84 remains sealed in. The relay R8 in FIG. 15D has not been energized, because contacts RM6 1g are open.

M85 Routine. In the overall execution of the M61 routine, however, the completion of the M86 routine results immediately in the execution of an M85 routine which means simply that the probes are retracted against the bias of their respective springs into their respective housings and thus free of the roll surface. This occurs in the present instance because pickup of the relay RZ at the time the rear probe signal E was reduced to zero results in closure of contacts RZ*a* (FIG. 15C) to complete a circuit through already-closed contacts RM61d to energize a relay RM85, the latter sealing in through its contacts RM85*a* and the already-closed contacts RM84*c*. Pickup of the relay RM85 opens the normally closed contacts RM85*b* to interrupt the holding circuit for relay RM84, so that contacts RM84*b* close to energize the solenoids RS and FS, thereby retracting the probes 81 and 112. Thus, when the relay RM85 is energized, in response to closure of the contacts RZ*a* when the contacts RM61*d* are closed (or for any other reason) the relay RM84 drops out to close contacts RM84*b*, thereby to retract the probes against their respective biasing springs.

After this occurs, the voltage E (FIG. 12) is no longer zero, so that relay RZ is deenergized, and the contacts RZ*a* reopen. Also, when relay RM84 drops out, its contacts RM84*c* open to break the holding circuit for relay RM85. The normally closed contacts RM84*d* and RM84*e* (FIG. 15A) thus reclose and permit centering movement of the main carriage 41 to proceed as described immediately below.

It will be seen that the M86 routine which is executed as part of an M61 routine brings the rear probe body toward the roll until the rear probe signal is reduced to a null. This locates the proximity switches PSR and PSL (FIGS. 4 and 5) adjacent the roll surface (although they may be at any location lengthwise of the roll), so that they are both actuated. The M85 routine which automatically follows the M86 routine causes the probes to be retracted, but the rear probe body remains in a position with the proximity switches close to the roll surface.

d. Movement of Wheel

to Center of Roll

As noted above, both of the proximity switches PSR and PSL are now actuated, because they sense the presence of the roll surface adjacent thereto. This means that the contacts PSR*a* and PSR*c* (FIG. 15A) are both closed, while the contacts PSR*b* are open. Similarly the contacts PSL*a* and PSL*c* are closed, but the contacts PSL*b* are open. Under these conditions, the potentiometer PT2 is connected between the lines 61+ and L2 via normally closed contacts RM84d, actuated contacts PSR*a* and normally closed contacts R2*a*. This applies a positive voltage across the potentiometer PT2, and its wiper thus supplies a relatively large, positive DC potential to the input of the amplifier or controller 126, causing the motor MZ to drive the main carriage 42 in a positive (right) direction along the Z axis at a relatively rapid or traverse rate. This traversing to the right by the carriage 42 may start with the rear probe assembly 80 and the wheel 21 initially disposed at any axial position along the roll. Such traversing in a positive Z direction will continue until the right proximity switch PSR moves just past the right end of the roll and thus becomes deactuated because it ceases to sense the adjacent metal of the roll surface.

When the switch PSR deactuates, its contacts PSR*a* open and its contacts PSR*b* close. As a result, the "traverse right" potentiometer PT2 is disconnected from the line 61+, but closure of contacts PSR*b* connects a potentiometer PT5 between the lines 61− and L2. Accordingly, the wiper PT5a of the latter potentiometer receives a relatively small negative potential, relative to ground or the line L2, and applies such poten-

tial to a negative input of the amplifier **126**. The motor MZ is energized to rotate at a relatively slow speed in a negative direction, i.e., such that it drives the carriage **42** to the left at a creep rate. When the potentiometer PT5 is excited, a relay R2 is simultaneously energized by conduction through a diode **212**, and this relay seals in through its own contacts R2*c* to the negative supply line **61**−. Thus, the normally closed contacts R2*a* are opened, and cannot serve to excite the potentiometer PT2 when the contacts PSR*a* reclose. Also, the normally open contacts R2*b* close so as to prepare a circuit for excitation of the potentiometer PT1, but the contacts PSR*c* are at this time deactuated and open.

After the carriage has been traversed to the right, as described above, the rear probe assembly **80** will be located at the right end of the roll as diagrammatically shown in FIG. **14**A. Thus, the proximity switch PSR has moved beyond the right edge of the roll and is deactuated, while the proximity switch PSL is still opposite the roll surface and remains actuated. Creeping of the carriage **42** to the left then begins, as described above, and continues until the proximity switch PSR is again disposed opposite the right edge of the roll (see FIG. **14**B) and is again actuated.

When the right proximity switch PSR is reactuated, its contacts PSRa close, but the potentiometer PT2 is not energized because the contacts R2*a* are now actuated and open. Its contacts PSR*b* open and thereby disconnect the potentiometer PT5 from the line **61**−. This terminates the creeping drive in a leftward direction by the motor MZ. Finally, the proximity switch contacts PSR*c* close to complete a series circuit through contacts RM**84***e*, actuated contacts PSR*c*, actuated contacts PSL*a*, actuated contacts R2*b*, and normally closed relay contacts R4*d*, thus connecting the potentiometer PT1 between the line **61**− and the line L2. As a result, the wiper PT1*a* supplies a relatively large and negative potential to an input of the amplifier **126** which energizes the motor MZ to drive the carriage **42** in a negative Z direction and at a relatively high or traverse rate.

However, even before such traversing begins, a relay R3 is energized by conduction through a diode **214**, and this relay seals in through its own normally open contacts R3*c* to the line **61**−. When the relay R3 picks up, its contacts R3*a* in FIG. **10** close thereby connecting the output terminal **180** of the pulser **178** to the "up" input of the bidirectional counter **166** through normally closed relay contacts R4*a*. It will be noted that at this time the contacts RM**61***e*, RM**61***f* and R4*b* are all open so that pulses produced by the pulse generator Pz as the result of the carriage **42** moving to the left will be supplied to the "up" input terminal of the counter **166** which was preset to contain a zero count as a part of the original setup procedure.

Thus, while the tool member or wheel **21** was initially moved to the right until the proximity switch PSR ceased to sense the adjacent roll surface (FIG. **14**A) and was then moved slowly back to the left until the proximity switch PSR again sensed the roll surface (FIG. **14**B), the carriage **42** and the wheel **21** are thereafter traversed to the left toward the left end of the roll. But during this latter movement in a negative direction along the Z axis, the distance moved by the carriage is measured and signaled by the registering of counts in the bidirectional counter **166** of FIG. **10**. The traversing of the carriage **42** to the left and the registering of counts from the pulse generator Pz in the counter **166** will continue until the proximity switch PSL moves beyond the left edge of the roll (FIG. **14**C) and becomes deactuated. At that time the number contained in and signaled by the bidirectional counter **166** will represent the distance moved by the rear probe assembly **88** from its position shown in FIG. **14**B to its position shown in FIG. **14**C.

When the left proximity switch PSL reaches the position illustrated by FIG. **14**C, it will be deactuated. As a result, the contacts PSL*a* will open, deenergizing the potentiometer PT1, so that the motor MC is stopped. However, the contacts PSL*b* will close to complete a circuit from the line **61**+ through a potentiometer PT6 to the line L2. Accordingly, a positive voltage will appear on the wiper PT6*a* and will be applied to a positive input of the amplifier **126** so that the motor MZ will begin driving the carriage **42** to the right. The wiper of the potentiometer PT6 is set to make this voltage a relatively small fraction of that appearing between the lines **61**+ and L2, so that the movement of the carriage to the right proceeds at a relatively slow or creep rate. Even before such creeping to the right begins, however, the closure of the contacts PSL*b* will result in energization of a relay R4 by conduction through a diode **215**, the relay sealing in through its normally open contacts R4*c* leading to the line **61**+. When the relay R4 picks up, its normally closed contacts R4*a* in FIG. **10**A open to break the previous connection to the "up" input terminal of the counter **166**; but its contacts R4*b* close to connect the output line **179** to the "down" input terminal of that counter. Therefore, as the carriage **42** creeps to the right in response to the voltage applied to the amplifier **126** from the potentiometer PT6, the pulses from the pulse generator Pz will be supplied to the "down" input terminal of the counter **166** and will diminish the count previously accumulated therein.

The carriage **42** will creep to the right until the rear probe assembly **80** reaches the position shown in full lines by FIG. **14**D and the left proximity switch PSL is again actuated due to sensing the left edge of the roll. Since the movement of the carriage and the rear probe assembly **80** from the position shown in FIG. **14**B to that shown in FIG. **14**C was registered positively in the counter **166**, and the distance moved by the assembly **80** in moving from the position shown in FIG. **14**C to that shown in **14**D was registered negatively, the counter **166** now holds and signals a number C which represents the spacing or lengthwise distance between the positions occupied by the probe **81** shown respectively in FIGS. **14**B and **14**D.

As noted above, when the rear probe assembly **80** has been moved to the right the position shown by FIG. **14**D, the switch PSL is again actuated. Its contacts PSL*a* thus close, but this produces no effect because the contacts R4*d* are now open. Its contacts PSL*b* open to deenergize the potentiometer PT6, so that creeping drive to the right by the motor MZ is terminated. Its contacts PSL*c* (FIG. **15**B) close, and because the contacts R4*b* are now closed, a voltage is supplied from the line **61**+ through normally closed contacts R6*b* to a differentiating circuit **216** which thereupon produces a short voltage pulse on a control terminal *a*. As a result, an enabling signal is applied to the terminal *a* in FIG. **10** to momentarily open the readout gates **168**, and the number C then held in the counter **166** is transferred to the input bus IB and thus to the input of the computer **165**. The computer contains appropriate means to store the number C thus fed to its input, and such number is signaled on the output bus OB. After a short time delay measured off by a time delay device TD1 (FIG. **15**B) the same input voltage applied to the differentiator **216** is supplied to a second differentiator **218** which produces a short voltage pulse on a control terminal *v*. This voltage signal is thus applied to the terminal *v* in FIG. **10**, and conditions the computer **165** so that it divides the number C by two and signals the result on the output bus OB.

The same input voltage supplied to the differentiator **218** is passed through a second time delay device TD2 to another differentiator **219** which then produces a short output voltage on its associated terminal *b*. This voltage appears on the terminal *b* in FIG. **10** to momentarily open the presetting gates **174**, and thereupon to set the counter **166** so that it holds and signals the number (i.e., C/2) then signaled on the output bus OB. By this procedure, therefore, the bidirectional counter **166** is first caused to store and represent the dimension C shown in FIG. **14**D, and that same counter is then positively set to hold one-half of its original number, i.e., to store and signal a number representing one-half of C as shown in FIG. **14**E.

The input voltage supplied to the differentiator **219** is also passed through another time delay device TD3 to energize a relay R5 (FIG. **15**B). Thus, the relay R5 picks up a short time after the counter **166** has been set to hold the number C/2, and this relay will remain energized so long as the circuit

through contacts R6*b*, PSL*c*, and R4*b* remains complete. When the relay R5 picks up, its contacts R5*a* in FIG. 15A close so that the potentiometer PT2 is again connected via the normally closed contacts RM84*d*, the actuated contacts PSR*a* and the contacts R5*a* between the lines 61+ and L2. Thus, a relatively large positive voltage appears on the wiper PT2*a* and is fed to the amplifier 126 so that the motor MZ is caused to drive the carriage 42 at a traverse rate toward the right.

While the traversing of the carriage in a right direction proceeds, the contacts R4*b* in FIG. 10 are still closed, so that pulses from the generator Pz appearing on the line 179 are fed to the "down" input terminal of the counter 166. Means are provided to terminate the traversing of the carriage when the number contained in the counter is reduced to zero. For this purpose, a zero decoder 220 is connected to the output conductors of the counter 166 and, in well known fashion, produces an output signal ZS only when the number held in and signaled by the counter is zero.

When the signal ZS appears, it is transferred through the now-closed relay contacts R5*b* in FIG. 15B to energize a relay R6 which seals in via its contacts R6*a* leading to the line 61+. In consequence, the normally closed contacts R6*b* open, thereby deenergizing the relay R5, and causing the contacts R5*a* in FIG. 15A to open. Thus, the motor MZ is deenergized and the carriage 42 is stopped with the probe assembly 80 positioned, as shown in FIG. 14E, with its probe located at the lengthwise center LC of the roll 22. Because the proximity switches PSL and PSR are spaced by equal distances S from the probe 81 (see FIG. 5), the carriage 42 will be stopped with the rear probe assembly 80 and the center of the wheel 21 at the lengthwise center of the roll, after moving to the right from the position shown in FIG. 14D through a distance C/2 to the position shown in FIG. 14E. Thus, when the carriage 42 is stopped the center of the face of the wheel 21 will be directly opposite the lengthwise center of the roll, that is, located one-half of the roll length from either edge of the roll, and irrespective of the particular length of the given roll 22 which is disposed in the grinding machine. This is the lengthwise center of the profile defined by the data contained in the profile tape 121, and at which the Z axis position is to be considered zero.

As shown in FIG. 15B, at the same time that the relay R6 is energized to terminate the positive movement of the carriage 42, a voltage signal is applied to a control terminal *c*. Thus, a signal is applied to the control terminal *c* of the director 125 in FIG. 6B, and such signal is used to set all Z axis storage devices and circuits inside the director to a zero or reference condition. Simultaneously, this signal sets all of the B and X axis storage devices and circuits of the director to a zero condition, since the wheel 21 is then at the center of its ranges of motion along the B and X axes.

Finally, as shown in FIG. 15B, when a voltage is applied to the relay coil R6, it is also applied to a time delay device TD4 which after a short delay energizes a relay R7. Pickup of the relay R7 opens its normally closed contacts R7*a* (FIG. 15A) to interrupt the holding circuit from the relay RM61. Accordingly, the relay RM61 is deenergized, and the execution of the center finding and the reference setting routing is completed. The contacts RM61b and RM61c open to remove the supply voltages from the lines 61+ and 61−, so that the limit switches LSB1, LSB2 can no longer affect the motor MB; the limit switches LSX1 and LSX2 can no longer affect the motor MX; the potentiometers PT1, PT2, PT5 and PT6 can no longer affect the motor MZ; and the relays R2, R3, R4, R5, R6 and R7 are all deenergized. When the relay R7 is momentarily energized prior to drop-out of relay RM61, the contacts R7*b* and RM61*g* in FIG. 15D are both closed for an instant, and the relay R8 picks up momentarily to close its contacts R8*a*, causing delay device TD5 to thereafter pulse a differentiator 221 so a positive-going pulse appears on the terminal *g*. This pulse is a "completion signal" indicating that execution of the M61 routine has been completed, and it appears on terminal *g* in FIG. 6B to restart the tape reader 131.

In review, the response of the control system to the reading of a block on the sequence tape 130 containing a command code M61 is (*a*) to locate the wheel 21 in the center of its ranges of travel along the B and X axes, (b) to advance the proximity switches into an operative position adjacent the roll surface, (c) thereafter to move the carriage 42 to sense the locations of the right and left edges of the roll and thence to move the carriage 42 until it is located midway between those edges, and (d) to set the contouring director 125 such that with the wheel 21 located at the lengthwise center of the roll the Z, X and B axes, control circuits therein are conditioned for a zero or reference position.

It might be noted briefly that an alternative and equivalent procedure may be employed to locate the wheel 21 at the lengthwise center of any particular roll. Instead of reading out the number C from the counter 166 (FIG. 10) into the computer 165 and dividing that number by two, the original number C could be left in the counter and circuitry (not shown) could be enabled such that the counter would respond to feedback pulses supplied to its "down" input terminal by registering a double count for each pulse. In this way, the number contained in the counter would be reduced to zero when the probe assembly 80 has been translated from the position shown in FIG. 14D to the position shown in FIG. 14E. It would be unnecessary to perform a dividing operation in the computer 165.

3. Automatic Alignment of the Roll Axis

Any roll, whether tapered or not, when placed in the steadyrest of the grinding machine 20 may not have its axis aligned with the Z axis of motion. And, unless the roll axis is made parallel with the Z axis, without regard to whether the roll surface is parallel to the Z axis, then a tapered shape will result on the roll after grinding has been completed. The term "tapered" is here used to designate a roll having no crown but progressively decreasing in diameter from one end to the other, and also to designate a convex or concave roll which is worn or machined such that its diameters are unequal at points spaced equally from the lengthwise center of the roll.

In this instance, the axis of a roll is automatically aligned in the grinding machine by apparatus and controls which need include only one roll surface sensing device, here exemplified by the rear probe assembly 80, which serves not only to sense the magnitude and direction of any misalignment but also to control the adjustment which is necessary to achieve alignment.

The alignment procedure embraces several steps which may be generally outlined as a prelude to a description of each in detail. First, gaging bands are ground at points spaced equally and in opposite directions from the lengthwise center of the roll, and preferably near the two ends of the roll. This results in gaging surfaces on the front side of the roll which lie along a line parallel to the Z axis; but if the roll axis is misaligned, these gaging surfaces will lie along the line at the rear side of the roll which is skewed relative to the Z axis. Second, the difference in the distances of the two gaging surfaces on the rear side of the roll from a line parallel to the Z axis is sensed and signaled by the rear probe assembly. The sense of this difference designates the direction of axis misalignment, and the magnitude of this difference indicates the extent of misalignment. One of the two steadyrests is then moved to swing the roll and its longitudinal axis about a point at the other steadyrest until the same signaled difference is reduced to a predetermined fraction of its original value, such fraction being based upon the spacing of the gaging bands relative to the pivot point. The foregoing will become more clear from the detailed descriptions which follow.

a. Startup Operations

At the end of the center finding routine executed in response to reading of an M61 code as described above, a completion signal on terminal *g* (FIGS. 15D and 6B) restarts

the tape reader **131** so that the next block on the sequence tape is read and signaled. In the designations of data blocks which follow, it should be kept in mind that these are only exemplary and that indeed the various codes or departure commands may appear in any appropriate order other than that here listed. Moreover, the blocks to be listed by way of example may be broken into a larger number of separate blocks if that is desirable to fulfill a system requirement that each block contain only one G code or one M code. This next or second block on the sequence tape may contain startup or operating commands. It will be recalled that all of the motors on the grinding machine **20** have thus far been stopped, and it is desirable to initiate now the rotation of the roll **22** and the wheel **21** at predetermined speeds. Thus, the second block on the sequence tape will contain the following codes in succession:

NO2	(block no.)
S24	(roll speed)
W40	(wheel speed)
M04	(start MH)
M17	(start MW)
P4	(delay duration)
G04	(time delay)
EOB	(end of block)

The block number code **N02** when signaled at the output terminals of the tape reader **131** produces no response in the system, although apparatus (not shown) may be provided to signal and display the block number in order to permit any particular block number to be located on the tape.

The **S24** code when read and signaled at the output of the tape reader **131** results in storage of the number "**24**" in the storage device **143**, thereby designating that when the headstock motor MH is in operation, it is to have a speed which makes the roll **22** turn at 24 r.p.m. Signals from the storage device **143** makes the voltage *Vs* of proper magnitude such that the amplifier or controller **156** will energize the motor MH whenever the contacts **RM04***b* are closed, and so that the roll **22** will be driven at 24 r.p.m.

When the **W40** code is read and signaled at the output of the tape reader **131**, it results in the storage of the number "**40**" in the device **144**, so that the voltage *Vw* from the converter **154** is of a magnitude to make the controller or amplifier **158** energize the wheel motor MW to drive the wheel **21** at a speed of 400 r.p.m. This energization of the motor MW will occur, however, only when the contacts **RM17***b* are closed.

When the next code **M04** is read and signaled at the output of the tape reader **131**, a momentary voltage will appear on the output terminal **M04** of the decoder circuits **134**. This voltage will appear on the same terminal in FIG. **15C**, resulting in pickup of the relay **RM04** which seals in through its normally open contacts **RM04***a*, and the normally closed contacts **RM05***a*. With this, the contacts **RM04***b* in FIG. **6B** close so that the motor MH is energized and begins to drive the roll **22**.

When the code **M17** is read and signaled at the output of the tape reader **131**, this results in a momentary voltage appearing on the output terminal **M17** of the decoder circuits **134**. This momentary voltage appearing on the same terminal labeled **M17** in FIG. **15C** results in pickup of a relay **RM17** which then seals in through its own contacts **RM17***a* and normally closed contacts **RM18***a*. With this, the contacts **RM17***b* in FIG. **6B** close so that the motor MW is energized and begins to rotationally drive the wheel **21**.

G04 Delay Routine. Some finite time will be required for the motors MH and MW to accelerate and reach the speeds commanded by numbers held in the respective storage devices **143** and **144**. Accordingly, a time delay is preferably introduced so that the motors reach their desired speeds before operations continue. The **P4** and **G04** codes contained in the second block as listed above serve this purpose. When the code **P4** from the second block is read and signaled by the tape reader **131**, this is stored in the P storage device **146** (FIG. **6D**) which has four output terminals connected to the similarly labeled control terminals of a dwell timer **225** in FIG. **15C**. The dwell timer has four control terminals **P1–P4** and, when started, it will measure off a dwell interval which corresponds in duration to the particular one of the control terminals which is then energized. In the present instance, the number contained in a P code and stored in the device **146** is the number "**4**," so that the **P4** output terminal will receive an enabling signal thereon. Accordingly, the dwell timer, when started, will measure off a relatively long interval from the instant that the contacts **RG04***b* close until it produces an output voltage which serves to energize the relay **R9**.

When the **G04** code is read and signaled, the output terminal **G04** of the decoder circuits **134** receives a momentary voltage which is applied to the correspondingly labeled terminal **G04** in FIG. **15C**. Accordingly, a relay **RG04** picks up and seals in through its own contacts **RG04***a* and normally closed contacts **R9***a*. At the same time, relay contacts **RG04***b* close to energize the dwell timer **225** so as to start it on a timing operation.

When the relay **R9** picks up after the dwell time delay, its contacts **R9***a* open to break the holding circuit for the relay **RG04**, and the latter thus drops out. This same voltage applied to the relay **R9** is also passed through normally closed relay contacts **RM02***g* to a control terminal *g* connected to the similarly labeled terminal in FIG. **6B**. This voltage serves to start the tape reader **131** so that it begins reading the next block on the sequence tape **130**. The time delay introduced by the dwell timer **225**, however, serves to prevent restarting of the tape reader **131** until the motors MH and MW have had time to accelerate up to the speeds commanded by the **S24** and **W40** codes contained in the second block.

As the tape reader **131** begins reading the third block or third sequence command, the wheel **21** and the roll **22** are being rotationally driven at predetermined speeds, e.g., 400 r.p.m. and 24 r.p.m., respectively. The wheel **21** is at this time retracted free of the roll surface because the cross slide **40** was placed in a retracted position during the initial setup procedure. Also, at this time the wheel **21** is still located opposite the lengthwise center LC of the roll **22**, that is, in the position labeled **21(1)** in FIG. **7**. The tape reader then begins reading the third block of information from the sequence tape **130**.

b. Movement of Location of First Gaging Band

As a specific example which will facilitate the present description, let it be assumed that the roll **22** is to be ground with a useful surface 156 inches in length (FIG. **7**). The actual length of the roll may be greater, but the precise locations of its opposite ends, which are relieved or reduced in diameter, are immaterial. It will also be assumed that the wheel **21** is 4 inches in width. For a roll to be finished with a useful length of 156 inches, it may be decided to grind gaging bands located 3 inches in from the ends of that surface. However, since the wheel is 4 inches in width, the centers of those gaging bands *b***1** and *b***2** will be located 5 inches inwardly from the ends of the roll surface as shown in FIG. **7**. To bring the wheel from its center position at **21(1)** to a position opposite the location of the desired gaging band *b***1**, therefore, it is necessary to move the wheel to the right along the Z axis through a distance of 73 inches.

With this understanding of exemplary dimensions, the next or third block of data read from the sequence tape may contain the following coded data:

NO3	
F120	(feed rate)
Z+073.000	(Z displacement)
G51	
EOB	

An F code contained in any block of the sequence tape designates the feed rate at which the director is to cause the wheel to be moved along the profile path. When the **F120**

code is read and signaled by the tape reader **131** (FIG. 6B), the number "**120**" is stored in the device **142** which then supplies digital output signals to the input terminal F of the director **125**. In the present instance, these signals will cause the director to make the wheel move at a feed rate of 120 inches per minute whenever the wheel is being controlled by the director to move along the profile path.

When the Z displacement number is read and signaled from the third block of the sequence tape, the number +073.000 is stored in the register **140** and is signaled by the latter as an input to the director **125**. This signaled Z displacement number represents a distance to be traveled by the wheel along the Z axis when the director is operating under the control of the profile tape **121**. The mere storage of the F and Z codes, however, does not cause the director **125** to begin operation.

G51 Routine. The G51 code designates that the system is to make the wheel **21** follow the profile data until it has moved along the Z axis in a direction and through a distance corresponding to the sign and magnitude of the number then stored in the Z register **140**. When the G51 code is read, a momentary voltage appears on the output terminal G51 of the decoder circuits **134**, and thus appears on the same terminal G51 in FIG. 15D. Accordingly, a relay RG51 is energized and seals in through its own normally open contacts RG51*a* and normally closed contacts R8*c*. A positive voltage is thus applied to a control terminal *e* which connects to the director **125** (FIG. 6B), conditioning the latter to cause movement of the wheel **21**, by the use of profile data on the tape **121**, until the wheel has moved through an incremental distance equal to that stored in the Z register **140**.

When a control voltage thus appears on the *e* control terminal of the director **125**, the latter supplies a start signal to the tape reader **122** which then reads the first block of contouring data from the profile tape **121**. Accordingly, the wheel **21** begins moving to the right along the Z axis, with coordinated motions along the X and B axes, although the wheel is not at this time in contact with the surface of the roll **22** and no grinding occurs. The director **125** and the sequence tape reader **122** continue to operate in normal fashion so that the profile tape **121** is read one block at a time and the wheel **21** moves progressively to the right while following the three axis profile. When the wheel has moved from its starting position through a distance of 73. 000 inches along the Z axis, however, the operation of the director **125** is terminated, the motion of the wheel stops, and the director produces a momentary voltage on its control terminal *f*, thereby signifying that the commanded G51 routine has been fully executed and that the wheel has followed the profile while moving in a positive direction along the Z axis through a distance corresponding to that stored in the register **140**, namely, 73. 0000 inches.

When a momentary voltage appears on the *f* terminal at the director **125**, this voltage is applied to the correspondingly labeled terminal in FIG. 15D and passes through the now-closed contacts R51*b* to energize the relay R8. In consequence, the contacts R8*a* close so that after a short time delay the time delay device TD5 energizes the differentiator **221** to produce a voltage pulse on the control terminal *g*. This voltage pulse, as explained before, serves to restart the sequence tape reader **131**, so that reading of the next or fourth block of data on the sequence tape begins. Also, at the time the relay R8 is energized, its contact R8c open to break the holding circuit for the relay RG51, and the latter drops out. The control circuitry of FIGS. 15A–G is thus restored to its original condition following the execution of the commanded G51 routine.

The wheel **21** has now been positioned at the location labeled **21** (2) in FIG. 7, although it is retracted away from and is not in contact with the roll surface.

c. Bringing the Wheel into Touching Contact With the Roll

The fourth block on the sequence tape is now being read. It will contain a code M70 which designates that the cross slide **40** is to be moved inwardly until the wheel touches the surface of the roll. The fourth block may contain simply the following coded data:

N04
M70
E0B

M70 Routine: When the M70 code is read and signaled from the fourth block of data on the sequence tape **130**, a momentary voltage will appear on the output terminal M70 of the decoding circuit **134**. This voltage will also appear on the same terminal in FIG. 15D, causing the relay RM70 to pick up and to seal in through its own contacts RM70*b* and normally closed contacts CS*b*. As a result, the contacts RM70*c* also close. At this time the feeler **76** (FIG. 6A) will not be touching the surface of the roll **22** and the limit switch LS1 will be deactuated. Accordingly, the normally closed contacts LS1*a* in FIG. 15D will be closed, so that a potentiometer PT9 will be connected between the lines L1 and L2, creating a positive voltage on its wiper PT9*a*. This positive voltage applied to an input terminal of an amplifier or motor controller **226** will cause the latter to energize the cross slide motor MC so that it rotates rapidly in a direction to traverse the cross slide **40** inwardly toward the roll **22**. When the feeler **76** (FIG. 6A) reaches the surface of the roll (and prior to the time that the wheel **21** touches the roll) the limit switch LS1 will be actuated, so that the contacts LS*a* and LS1*b* in FIG. 15D will be respectively opened and closed. With this, the potentiometer PT9 is deenergized, and a circuit is established through normally closed contacts CS*c* to excite a feed potentiometer PT10. Accordingly, a smaller positive voltage appears on the wiper PT10*a* and is applied to an input of the amplifier or controller **226** so that the motor MC continues to drive the cross slide inwardly, but at a feed or creep rate.

Up to this time, the wheel **21** has been turning freely in air, having no contact with the roll **22**. The wheel motor MW has thus been operating under no load conditions, the current drawn thereby has been relatively small, the voltage across the load-sensing resistor **159** (FIG. 6B) has been small, and the current sensing relay CS has been deenergized. However, as the wheel **21** makes initial contact with the surface of the roll **22** by virtue of the inward feeding of the cross slide **40**, a load is imposed on the motor MW and it draws increased current. Accordingly, the sensitive, current sensing relay CS is picked up. Its contacts CS*c* open to deenergize the potentiometer PT10, thereby stopping the cross slide motor MC; its contacts CS*a* (FIG. 15D) close to complete a circuit through the now-closed contacts RM70e so that relay R8 is picked up and its contacts R8a close to create a tape reader staring voltage on the control terminal *g;* and its contacts CSb open to drop out the relay RM70. Thus, the M70 routine of bringing the wheel into initial contact with the work by movement of the cross slide has been completely executed, and the sequence tape reader **131** has been restarted so that reading of the next block of the sequence tape begins.

d. Grinding Right Gage Band to Predetermined Depth

With the wheel **21** just touching the roll **22**, the next block on the sequence tape commands movement of the wheel inwardly along the X axis so that a smooth gaging band or surface will be ground to a depth predetermined by the sequence programmer. Usually, the gaging band will be smooth and accurate if ground to a depth of 0.005 inch. The next block on the sequence tape will thus contain the following data:

N05
F005
X–0.0050

G01
E0B

When the F and X addresses and the numbers following them are read and signaled by the tape reader **131**, they are stored in the F and X storage registers **142** and **141** (FIG. 6B). In the present instance, that X command is −.**0050**, indicating that a 0.005 inch increment of movement by the wheel inwardly along the X axis is desired. The storage register **141** supplies this X command information to the director **125**, but the director does not begin operation at this time.

G01 Routine. The tape reader then reads and signals the G01 code and the E0B code, the latter causing the tape reader **131** to stop. When the code G01 is signaled by the reader **131**, it causes the momentary appearance of a voltage on the G01 terminal of the decoder circuits **134**. This voltage appearing on the terminal G01 in FIG. 15E causes the relay RG01 to pick up and seal in through its own contacts RG01a and normally closed contacts R8d and R17c. A voltage is thus established upon the control terminal *d* which is a control terminal for the director **125** in FIG. 6B. A signal on the control terminal *d* conditions the director **125** such that it will cause movement of the wheel at the commanded low feed rate (5 inch/min.) along the X axis in the direction and through a distance represented by signals from the X storage register **141**. Accordingly, the director does not start the tape reader **122** but begins producing an output signal on its X output terminal such that the motor MX is energized to move the wedge **65** inwardly, thereby to move the wheel **21** inwardly along the X axis. When the inward movement of the wheel equals the stored commanded displacement (here, 0.005 inch), then the director terminates the energization of the motor MX and supplies a signal on its control terminal *h*, indicating that the commanded G01 routine has been fully executed. This signal on the control terminal *h* appears on the correspondingly labeled terminal in FIG. 15D, passes through the normally closed contacts RG55*c* and thus momentarily energizes the relay R8. Accordingly, the contacts R8*a* close and a voltage pulse appears on the control terminal *g*, thereby restarting the sequence tape reader **131**. The contacts R8d open to unseal the relay RG01, and the relay R8 is then deenergized.

It will thus be seen that in response to the reading of a G01 sequence command, the director causes the wheel **21** to be moved along the X axis in a direction and through a distance corresponding to the data then held in the X storage register **141**. In the present instance the wheel started from a position in which it was just touching the surface of the roll **22** and moved inwardly a distance of 0.005 inch, thereby grinding a smooth gaging band *b*1 (FIG. 7) with a depth of 0.005 inch near the right end of the roll **22**. When the grinding of the gage band has thus been completed, the sequence reader **131** is restarted.

e. Movement of Wheel to Location of

Left Gage Band

The next block of data on the sequence tape commands withdrawal of the wheel along the X axis through a predetermined distance so that the wheel will clear the roll surface as it is moved lengthwise of the roll. For this purpose, the next block of data may include:

N06
X+.0250
G01
E0B

It will be seen that the sixth block of data set forth above represents a G01 command calling for the wheel to be moved outwardly along the X axis through a distance of 0.0250 inch. When the X data is read it replaces the information previously stored in the X register **141**. When the G01 code is read, the same routine of operations previously described above in connection with the G01 code is performed, with the tilting platform **35** being moved downwardly to withdraw the wheel through a distance of 0.0250 inch. Thus, the face of the wheel is not only withdrawn the distance of 0.005 inch (which is the depth of the right gaging band *b*1), but it is then withdrawn an additional 0.0200 inches so as to clear the roll surface. When this withdrawal of the wheel is complete, the tape reader **131** is restarted, as explained above, so that the reading of the next block of the sequence tape begins.

The next block of information on the sequence tape commands movement of the wheel from the axial location shown at **21**(2) to the location shown at **21**(3) in FIG. **7**, so that the wheel will then be disposed lengthwise at a position for the grinding of the left gage band *b*2. This next block of data may include:

N07
F120
Z−146. 0000
G51
E0B

This seventh block of data calls for the execution of a G51 Routine wherein the wheel **21** is to be moved at a rate of 120 inch/min. along the profile stored on the profile tape from its initial position **21**(2) in FIG. **7** through a distance of 146 inches to the left to the position shown at **21**(3). Thus, when the F and Z numbers are read and signaled they replace the data previously stored in the registers **142** and **140**, and when the code G51 is read and signaled it causes the sequence of operations previously described as a G51 Routine, except in this case the wheel is moved to the left along the Z axis through a distance of **146** inches while following the contoured profile. At the end of this operation, the tape reader is restarted to begin the reading of the next block.

f. Grinding of the Left Gaging Band

The next block of data on the sequence tape contains the following command information:

N08
F005
X−0. 0250
G01
E0B

The data listed above involves the execution of a G01 Routine in which the wheel is to be fed slowly inwardly toward the roll through a distance of 0. 0250 inch. This G01 Routine is executed in the manner previously described, and it will be apparent that the wheel is thus moved inwardly to the same position along the X axis as that which it occupied at the time when the grinding of the right gaging band was completed. In other words, the center of the wheel face at the completion of the grinding of the left gaging band *b*2 has a position which lies along a line **230** (FIG. 7) extending to the center of the right gaging band and which is parallel to the Z axis of the grinding machine. The left gaging band *b*2 may be slightly greater or less in depth than the gaging band *b*1 at the right end of the roll, but the gaging band surfaces at the front of the roll **22** will lie along a line which is parallel to the Z axis.

During the grinding of the two gaging bands, the rear probe **81** has been retracted clear of the roll surface, and it remains in that retracted position.

g. Retraction of the Wheel

Free of the Roll

After the left gaging band *b*2 has thus been ground and the G01 routine has been executed as explained immediately above, it is desirable to retract the wheel **21** so that it is clear of the roll surface. For this purpose, the cross slide **40** is retracted to the limit of its travel in response to a sequence command M71. For this purpose, the next block of the sequence tape **130** may contain the following data:

N09
P3
G04
M71
E0B

When the P3 code is read and signaled, the number "3" replaces that previously held in the P storage device **146**. When the G04 code is read, a G04 time dwell routine, as heretofore described, is initiated so that the dwell timer **225** (FIG. 15C) will produce an output signal on the control terminal *g* after a predetermined time interval has elapsed. It is during this interval that the M71 Routine is executed as hereinafter described.

M71 Routine. The tape reader **131** completes the reading of the ninth block by producing a momentary signal on terminal M71 of the decoder circuits, and then stops when the code E0B is read. When the M71 signal appears on the same terminal in FIG. 15D, it causes pickup of the relay RM71 which then seals in through its own contacts RM71*a* and the contacts RG04*c*, the latter now being closed because the relay RG04 is energized during the dwell time interval being measured off by the dwell timer **225** in response to the previously read G04 code. Pickup of the relay RM71 results in closure of contacts RM71b to complete a circuit from the negative voltage supply line L3 through the normally closed contacts LSC*a* thereby applying a negative excitation voltage to a potentiometer PT11. Accordingly, a negative voltage appears on the wiper PT11*a* and is fed to the controller or amplifier **226** so that the motor MC is energized to rotate in a direction and at a relatively high speed so as to traverse the cross slide **40** outwardly or away from the roll **22**. If the cross slide reaches the outward limit of its travel before the dwell timer **225** times out, the limit switch LSC will be actuated to open its normally closed contacts LSCa, thereby deenergizing the potentiometer PT11 when the cross slide reaches a fully retracted position. But when the dwell timer **225** times out and produces a signal on the control terminal *g* to restart the sequence tape reader **131**, the relay RG04 will drop out, as previously explained, and thus the contacts RG04*c* will open to break the holding circuit for the relay RM71. Thus, the execution of the M71 Routine has been completed with the cross slide being retracted and the tape reader **131** having been restarted so that the reading of the next block of the sequence tape is begun.

h. Sensing the Location of the Left Gaging

Band on the Rear Side of the Roll

The next operation to be performed is to bring the rear probe assembly **80** into operative relationship with the roll so that it senses the left gaging band *b*2 and is conditioned to produce a reference or null signal. The code M86 calls for operations of releasing the rear probe so it is biased toward the roll, then driving the rear probe body until the LVDT95 associated therewith produces a null or zero signal. Thus, the next block of data which is now being read from the sequence tape **130** contains simply the following command data:

N10
M86
E0B

When the code M86 is read and signaled by the sequence tape reader **131**, it results in a momentary voltage appearing on the M86 output terminal of the decoder circuits **134**. Accordingly, a momentary voltage appears on the same terminal labeled M86 in FIG. 15B. This produces the same operations described above as an M86 Routine with reference to block N01. That is, the relay RM86 picks up and seals in through the contacts RM86a and the normally closed contacts RZ*b*. The RM86*b* contacts therefore close to energize the relay RM84 (FIG. 15C) which seals in through its own contacts RM84*a* and the normally closed contacts RM85a. As a result, the normally closed contacts RM84*b* open to deenergize the solenoids FS and RS, so that the rear probe is biased forwardly by its spring **92** (FIG. 4).

At this time the contacts RM84*e* in FIG. 15D close, but the relay R8 is not energized because the contacts RM86*d* are now open. Also, when the relay RM86 picked up and sealed in, its contacts RM86*c* (FIG. 15B) close to apply a positive voltage to the step pulse driver **211** so that the step motor MRG is pulsed to drive the rear probe body **88** inwardly toward the roll **22**. When the probe **81** engages the roll and is shifted inwardly relative to the body to a position at which the voltage E (FIG. 12) is reduced to zero, the zero detector **210** causes the relay RZ to be energized. This opens the contacts RZ*b* in FIG. 15B to unseal the relay RM86. Also, the contacts RZ*a* in FIG. 15*c* close, but this produces no effect upon the relay RM85 because the contacts RM61*d* are now open. Thus, the rear probe **81** has been extended, and the probe body has been positioned by its stepping motor MRG such that the rear probe assembly is producing a zero or null signal with the probe engaged at the rear side of the left gaging band *b*2.

When opening of the contacts RZ*b* drops out the relay RM86, the contacts RM86*b* also open but the relay RM84 remains sealed in through its contacts RM84*a* and normally closed contacts RM85*b*. The contacts RM86*d* close (FIG. 15D) thereby completing the circuit through the contacts RM61*h*, RG55*c*, RM86*d*, RM84*e* (now actuated) and RM85*d* to energize the relay R8. The contacts R8a close so that after the delay of TD5 the differentiator **221** produces a momentary positive voltage pulse on the control terminal *g* so that the sequence tape reader **130** is restarted. Accordingly, the next block of data on the sequence tape is read.

This next block of data simply commands that the rear probe **81** be retracted free of the roll be energization of the associated solenoid RS. Thus the next block now being read from the sequence tape includes:

N11
M85
E0B

When the code M85 is read and signaled, a momentary voltage appears on the M85 output terminal of the decoder circuits **134** to initiate an M85 Routine. This momentary voltage appears on the same terminal M85 in FIG. 15C, so that the relay M85 picks up and seals in through its contacts RM85*a* and the now-closed contacts RM84*c*. When the relay RM85 picks up and seals in, its contacts RM85b open to unseal relay RM84, thereby closing contacts RM84*b* to energize solenoids RS and FS. Contacts RM84*c* open to unseal and drop out relay RM85. In FIG. 15D, therefore, the contacts RM85*d* first open to drop out relay R8, but the opening of contacts R8*a* produces no positive voltage pulse on terminal *g*, so reader **131** is not restarted. Just after contacts RM85*d* open, contacts RM84*e* open, but during the interval that relay RM85 is energized, contacts RM85*e* are closed to apply a positive input voltage to delay device TD5*a*, which thereafter applies an energizing pulse to relay R8. The contacts R8a close momentarily, so a positive pulse is applied to the associated terminal *g* and the reader **131** is restarted. Thus the net result of the routine executed in response to an M85 code is simply that the previously sealed in relay RM84 is opened so that its contacts RM84*b* reclose to energize the solenoids RS and FS which in turn retract the probes **81** and **112** clear of the roll **22**. After this is accomplished the sequence tape reader **131** is restarted. It should be kept in mind that the probe body **88** remains in its position, relative to the housing **89**, reached as a result of the nulling operation previously described.

The probe **81** is now retracted free of the roll **22**, but resides opposite the left gaging band*b*2 (FIG. 7). The next operation is to return the carriage to the right so that the probe **81** is positioned opposite the right gaging band *b*1. For this purpose, the next block of the sequence tape **130** contains:

N12
F120
Z+146. 000
G51
E0B

When the data F120 and Z+146. 000 are read, they replace the information previously stored in the F and Z registers **142** and **140** (FIG. 6B). Then, when the code G51 is read, a G51 Routine is initiated and executed as described above, terminating in restarting of the tape reader **131** so as to begin the reading of the next block of the sequence tape. It will be re-

called that in the execution of a G51 Routine with the number Z+146. 000 held in the register 140, the director 125 will cause the wheel 21 to be moved along the profile defined by the profile tape 121 until the motion along the Z axis toward the right has amounted to 146 inches. The wheel then comes to rest with the rear probe 81 disposed opposite the center of the right gaging band *b*1 as shown in FIG. 7.

The next step is to release the rear probe 81 so that it engages the surface of the right gaging band *b*1. The next block of the sequence tape contains:

N13
M84
E0B

When the code M84 is read and signaled by the tape reader 131, a momentary voltage appears on the M84 output terminal of the decoder circuits 134. Accordingly, a momentary voltage appears on the same terminal shown in FIG. 15C so that the relay RM84 is picked up and seals in through its own contacts RM84*a* and the normally closed contacts RM85*b*. This is the beginning of the execution of an M84 Routine. That is, when the relay RM84 picks up, its contacts RM84*b* open to deenergize the solenoids RS and FS, so that the spring 92 biases the rear probe 81 (FIG. 4) outwardly into contact with the surface of the roll. The probe is thus engaged with the rear side of the roll at the right gaging band *b*1, and the LVDT95 associated therewith will be producing some finite output voltage unless the roll axis is not misaligned.

Referring to FIG. 8, a roll 22 having different diameters at locations near its opposite ends is there shown with a greatly exaggerated degree of taper. It is to be recalled that by the process of grinding the gaging bands *b*1 and *b*2, their surface midpoints at the front side of the roll lie on a line (see 230 in FIG. 7) which is parallel to the Z axis of the machine. Also, the body of the probe assembly 80 when located opposite the left and then the right gaging bands *b*2 and *b*1 lies along a line 232 (FIG. 8) which is parallel to the Z axis And in FIG. 8, it has been assumed and shown that the longitudinal axis 234 of the roll 22 is skewed or non-parallel relative to the Z axis, i.e., relative to a line 235 parallel to the Z axis drawn through a point C at which the roll is supported in the left steadyrest.

The dimension A represents the longitudinal distance between the point C and the location of the center of the left gaging band *b*2. This dimension is known by virtue of the programmed location of the left gaging band (−73 inches from the roll center, as shown in the example of FIG. 7) and a measurement performed on the roll itself. The dimension G represents the longitudinal distance between the centers of the two gaging bands, and this is selected and known (in the present example, 146″) at the time the sequence program is prepared. Thus, the dimensions A and G for any given roll are definitely known at the time of initial setup.

For a purpose to be made clear before, the value of a fraction is computed and fed into the control system. In particular, the value of the fraction (G−A/2G) is determined, and the calibrated dial 208 (FIG. 12) is adjusted to correspond to that value. Such adjustment sets the wiper 209a of the potentiometer 209 to multiply by the fractional value, i.e., so that when the input voltage Eo is applied across the potentiometer, the output voltage E′ takes on a value:

$$E' = (G - A/2G) \cdot Eo \quad (1)$$

This adjustment of the dial 208 and potentiometer 209 may be made at the time the roll 22 is being set up in the machine.

It will be recalled that with the probe assembly 80 in the left position shown in FIG. 8, the probe signal E (FIG. 12) was set to a reference or null value by adjustment of the probe body along the X axis, i.e., transverse to the Z axis. Then, without changing the X axis position of the probe body, the probe assembly was moved to the right position shown in FIG. 8, and the probe released to engage the surface of the gaging band *b*1. In its left and right positions, therefore, the probe body defines the reference line 232 parallel to the Z axis.

In consequence, the output voltage E (FIG. 12) derived from the probe assembly when in the right position illustrated by FIG. 8 is proportional to the difference between (a) the distance *p*1 from the reference line 232 to the surface of gaging band *b*2, and (b) the distance *p*2 from the reference line 232 to the surface of the gaging band *b*1. That is,

$$\Delta = p1 - p2 \quad (2)$$

where Δ is the difference in distances as shown in FIG. 8. Since the probe 81 is deflected inwardly by the distance Δ when in the right position as compared to its left position, the voltage E in FIG. 12 takes on an initial value Eo represented by the expression:

$$Eo = K\Delta \quad (3)$$

where *k* is a factor of proportionality

In the present instance, the initial voltage *Eo* is positive in polarity. However, if the probe 81 extended further from the probe body when in the right position as compared to the left position, the initial voltage *Eo* by its negative polarity would indicate the sense or sign of the difference Δ.

To bring the roll axis into alignment with the Z axis of the machine, the right steadyrest and thus the right neck of the roll must be moved forwardly or rearwardly along the X axis until the roll axis 234 coincides with the Z axis line 235. This means that the roll must be swung clockwise (in the example of FIG. 8) about the pivot point C by moving the right steadyrest forwardly until the point Q on line 234 coincides with the point T on line 235. In such aligning action the point Q on axis 234 must move through the distance *d* and thus the point F (on band *b*1 and engaged by probe 81) must likewise move through the distance *d* to the point labeled J. When that happens, the displacement of the probe 81 from a null position will decrease, and the probe signal E (FIG. 12) will decrease.

From inspection of FIG. 8, certain geometric relationships may be expressed. It will be seen that the difference between the diameters D2 and D1 at the right and left gaging bands is equal to the distanceΔ, viz:

$$D2 - D1 = \Delta \quad (4)$$

It follows that:

$$(D2/2) - (D1/2) = R2 - R1\ (\Delta/2) \quad (4a)$$

Also, the distanceΔis equal to the sum of the distance *d* and a distance *e* the latter being the spacing between point J and a line 236 drawn parallel to the Z axis from the center of the left gaging band. This may be expressed:

$$d = \Delta - e \quad (5)$$

Further, the distance K plus the distance *d* is equal to the radius R2 at the right gaging band, that is:

$$d = R2 - K \quad (6)$$

The two triangles CIH and CTQ are similar triangles, since their corresponding sides are parallel. Thus, the ratios of the lengths of corresponding pairs of sides are equal, and this may be written:

$$HI/CI = QI/CI \quad (7)$$

But the length HI is equal to (R1 − K); the length CI is equal to A; the length QT is equal to *d*; and the length CT is equal to (A+G). Substituting these dimensions into equation (7) yields:

$$R1 - K/A = d/A+G \quad (8)$$

The quantity $R1 - K$ can be expressed in different form by substitution from equations (4a), (5) and (6):

$$R1 - K = R2 - (\Delta/2) - K = d - (\Delta/2) = \Delta - e - (\Delta/2) = (\Delta/2) - e \quad (9)$$

Substituting $R1 - K$ from (9) and *d* from (5) into (8):

$$\frac{\frac{\Delta}{2} - e}{A} = \frac{\Delta - e}{(A+G)} \quad (10)$$

Simplifying equation (10) yields:

$$A\Delta - Ae = \frac{A\Delta}{2} + \frac{G\Delta}{2} - Ae - Ge \quad (11)$$

$$\frac{A\Delta}{2}=\frac{G\Delta}{2}-Ge \quad (12)$$

$$Ge=\frac{\Delta}{2}\cdot(G-A) \quad (13)$$

$$e=\Delta\cdot\frac{(G-A)}{2G} \quad (14)$$

Equation (14) indicates that to move the roll about the steadyrest pivot point C (FIG. **8**) so as to bring the roll axis **234** into coincidence with the line **235** parallel to the Z axis, the right end of the roll must be moved until the probe **81** and the point F are brought to point J, i.e., until the probe is deflected inwardly from its null position by a distance *e* which is equal to the original differenceΔmultiplied by the fraction $(G-A)/G$.

But the original difference$\Delta$is proportional to the original voltage signal Eo, as indicated by equation (3). And when the probe is deflected from a null position only by the distance *e*, the probe voltage signal E at that time will be proportional, i.e.,

$$E=ke \quad (15)$$

Thus, equation (14) can be rewritten:

$$(E/k)=(Eo/k)\cdot(G-A/2G) \quad (16)$$

$$E=Eo\cdot(G-A/2G)=E' \quad (17)$$

Thus, if the right steadyrest is moved forwardly, and the probe signal *E* is reduced until it becomes equal to the value *E'*, it will be known that the roll axis **234** is then aligned with the Z axis of the grinding machine.

Methods and apparatus for effecting such adjustment of the right steadyrest are provided. It will be recalled that after reading of the block **N13**, and the release of the probe **81** into engagement with the right gaging band *b*1, the sequence tape reader was restarted immediately. The next block on the sequence tape contains the following data:

N14
M64
E0B

The code **M64** represents a command to adjust the right steadyrest until the output signal E from the rear probe assembly is changed from its original value Eo to a predetermined fraction thereof, i.e., to a value E' as represented by equation (17).

When the **M64** code is read and signaled (and the tape reader **131** thereafter stops in response to the reading of the **E0B** code), a momentary voltage appears on the **M64** output terminal of the decoder circuits **134**. This momentary voltage appears also on the same terminal **M64** shown in FIG. **15E**, so that a relay **RM64** is picked up and sealed in through its contacts **RM64a** and normally closed contacts **R13a**. This results in energization of a time delay device **TD6** but during the time interval measured off by the latter, the contacts **RM64***b* in FIG. **12** close to supply the rear probe signal voltage E to the input of a memory amplifier **240**. At this time the probe signal E has the initial value previously designated *Eo* which represents the differenceΔ. Accordingly, the memory amplifier then charges a capacitor **240** therein such that the voltage thereacross agrees in polarity and magnitude with the probe signal voltage E. Memory amplifiers of this type are well known to those skilled in the art, and it will be sufficient to observe simply that when the rear probe signal voltage E is disconnected from the input of the memory amplifier **240**, the capacitor **240***a* will be held charged with the voltage *Eo* appearing thereacross. In the example represented by FIG. **8**, the initial difference voltage *Eo* will have the positive polarity labeled in FIG. **12**.

After the time delay produced by the device **TD6**, the relay **R11** (FIG. **15E**) will pick up and remain energized so long as the relay **RM64** is energized. Thus, the contacts **R11***a* in FIG. **12** will open to disconnect the probe signal voltage E from the input of the memory amplifier **240**. Also, the contacts **R11***b* and **R11***c* in FIG. **12** will close so as to complete connections to the input terminals of a summing amplifier **241**.

As previously explained, the potentiometer wiper **209***a* has been adjusted to a position such that the output voltage E' appearing thereon is a predetermined fraction $G-A/2G$ of the input voltage *Eo* applied to the entire potentiometer. Thus, it may be understood that the input voltage E' applied through the contacts **R11***b* to the input terminals on the left side of the summing amplifier **241** represents the final polarity and magnitude to which the probe signal voltage E must be adjusted in order to bring the roll axis into alignment with the Z axis of the machine. The voltage E from the rear probe assembly is applied through the now-closed contacts **R11***c* to the input terminal on the right side of the amplifier **241**. The amplifier produces on its output line a signal which is proportional to the difference (E—E') between the first input voltage E' and the second input voltage E. Initially the latter will have the value *Eo*. Therefore, the output voltage of the summing amplifier fed to the steadyrest motor MS will energize the latter causing it to drive the headstock forwardly, i.e., in a positive direction along the X axis and transversely to the Z axis (see FIG. **6A**). The steadyrest motor will continue to run and to move the right steadyrest. but as it does so the probe **81** engaged with the gaging band *b*1 (see FIG. **8**) will be biased by its associated spring outwardly relative to its probe body, so as to remain in contact with the gaging band surface. As a result, the probe signal voltage E will decrease in magnitude. When the steadyrest motor MS has moved the steadyrest to such an extend that the probe signal voltage E becomes equal to the voltage E', i.e., when (D—E') is zero, then the output of the summing amplifier **241** will become zero, and the steadyrest motor will stop. Thus, the steadyrest is stopped at a position in which the rear probe signal voltage E has been reduced from an initial value Eo to a lower value E', the latter being equal to the voltage Eo multiplied by the fraction $G-A/2G$. As indicated by the analysis given above, this results in the axis **234** of the roll **22** (FIG. **8**) being aligned parallel to the Z axis of the machine.

The steadyrest motor MS begins its adjusting drive at the time the relay **R11** (FIG. **15E**) picks up. At that instant, however, a time delay device **TD7** receives an input voltage, and during the period when the steadyrest motor is operating, the output from the device **TD7** results in pickup of a relay **R12**. The contacts **R12a** in FIG. **15E** therefore close, but the contacts **RZS***a* in series therewith are now open for a reason which will be explained below, and thus the relay **R13** will not be immediately energized.

In order to signal when the adjusting movement of the right steadyrest has been completed, a zero detector circuit **242** is connected to receive as its input the output voltage of the summing amplifier **241**. When this output voltage is reduced to zero and the motor MS is stopped, the zero detector circuit **242** energizes a zero-signaling relay **RZS**. It will be understood that during the time that the steadyrest motor is energized, the zero detector circuit **242** will be receiving a finite input voltage, the relay **RZS** will be deenergized, and thus the contact **RZSa** in FIG. **15E** will be open. However, as soon as the right steadyrest reaches its final position and the steadyrest motor MS is stopped, then the relay **RZS** will be energized to close the contacts **RZSa** in FIG. **15E**, completing a circuit through the now-closed contacts **R12a** so as to energize a relay **R13**. Accordingly, the contacts **R13***a* in FIG. **15E** open to break the holding circuit for relay **RM64**, and the relays **RM64**, **R11** and **R12** all drop out. With this, the relay contacts **RM64***b* in FIG. **12** open so that even though the contacts **R11***a* reclose, the probe signal voltage E is not again applied to the input of the memory amplifier **240**. Also, the relay contacts **R11***b* and **R11***c* reopen to interrupt the input circuits for the summing amplifier **241**.

When the relay **R13** is energized by conduction through contacts R12*a* and RZS*a*, a momentary voltage appears on the control terminal *g* in FIG. **15E**. This voltage serves to restart the sequence tape reader **131** and initiates the reading of the next block of data from the sequence tape **130**. Therefore, the complete alignment procedure has been fully carried out and the roll **22** is disposed in the grinding machine **20** with its central axis of rotation disposed parallel to the Z axis of the machine.

4. Determining Direction of First Grinding Pass; Initial Grinding

If any given roll **22** is "tapered," neither its front side nor its rear side will be parallel with the Z axis after the axis alignment operations have been performed. More precisely, the straight or contoured surface of the roll will be skewed relative to the Z axis, and the diameter of the roll near one end will be larger than that at the other end. If the right end has the larger diameter (as illustrated in FIG. **8**), then the rear probe voltage E will be of positive polarity when the axis alignment operations are completed; if the left end has the larger diameter, the polarity of the voltage E will be negative.

If the initial grinding pass of the wheel **21** lengthwise along the roll were always started from one end, in many instances the wheel would be forced to take a progressively deeper bite as it moves from that end of the roll having the smallest diameter toward that end with the largest diameter. This may cause damage to the expensive wheel **21**, since the programmer would have no way of knowing or determining in advance the maximum depth of the wheel bite. It is desirable therefore always to execute the first grinding pass by moving the wheel along the Z axis in a direction from the roll end of largest diameter toward that of smallest diameter, so that the depth of bite becomes progressively smaller and the wheel is not gouged into the roll.

Herein, the grinding of the roll surface is always initiated by movement of the wheel along the Z axis in a direction from the larger to the smaller diameter of the roll. For this purpose, means are provided to signal "right end larger" or "left end larger." As shown in FIG. **12**, a polarity trigger circuit **245** receives the rear probe signal voltage E and controls a relay R+. The trigger **245** energizes the relay when the voltage E is of positive polarity (i.e., when probe **81** is deflected into its body from a null position), and deenergizes the relay when the E voltage is zero or of negative polarity (i.e., when probe **81** projects toward the roll beyond a null position). During the execution of the M**64** routing to adjust the right steadyrest, as described above, the contacts RM**64***b* (FIG. **15E**) will be closed. The contacts R+*a* will be closed only if the diameter of the right gaging band *b***1** is larger than that of the left gaging band *b***2** (see FIG. 8), that is, if the probe **81** is still deflected into the probe body relative to the null position previously occupied by the probe when engaged with the left gaging band, thereby indicating that the right band radius **R2** is larger than the left band radius **R1**. Since the gaging bands are spaced equally along the Z axis from the lengthwise roll center LC, the radii **R1**, **R2** and the diameters **D1**, **D2** are supposed to be equal at the gage band locations. But if the axis of the roll, assuming it to be untapered, was initially misaligned, the grinding of the gage bands makes it appear, even after alignment, that the radii from the roll axis to the rear surface of the right gage band is either larger or smaller than the radius at the left gage band. Thus, during the execution of the M**64** alignment routine, the polarity of the probe voltage E is sensed, and a relay **R14** will be picked up or left deenergized, respectively, if (a) the right end of the roll is larger or (b) the left end of the roll is larger. If relay **R14** is energized because the "right end is larger," it seals in through its own contacts **R14***a* and normally closed contacts RM**19***b*, and in that event, the contacts **R14***b* close to energize a block delete relay RBD and to place a positive voltage on the control terminal *i*.

The next few data blocks on the sequence tape are best considered together, since some contain block delete codes DE. These blocks may be listed:

N15 DE M86 EOB
N16 DE M85 EOB
N17 DE Z−149.000 G51 EOB
N18 M19 EOB
N20 DE M85 EOB
N21 DE Z+003.000 G51 EOB
N22 M70 EOB

a. Right End Larger

Let it be assumed first that, as shown in FIG. **8**, the right end of the roll **22** is larger in diameter. Thus, when the M**64** alignment routine is completed (with the probe **81** engaged with the surface of band *b***1** and the cross slide **40** retracted so the wheel **21** is free of the roll), the relays **R14** and RBD will be picked up, and a voltage will be present on terminal *i* of the reader **131** (FIG. **6B**) to enable the latter to respond to any block delete codes which are read and signaled on the DE terminal of the decoder circuits **134**. When the M**64** routine is complete, the tape reader begins reading block **N15**, and first reads the DE code—so that a voltage is applied to the DE input terminal of the reader **131**. The appearance of a momentary voltage at DE when the terminal *i* is receiving an enabling voltage causes the reader **131** to suppress its output signals as the rest of the block is read, to keep the tape **130** moving when the EOB code in that block is read, but to begin reading the next block (if it does not contain a delete code DE) in normal fashion.

Therefore, the response to blocks **N15**, **N16** and **N17** is deleted since all contain a delete code DE (see above). The reader simply moves the tape **131** until it begins reading block **N18**.

When the **M19** code (signifying that the block delete operation is to be disabled) is read and signaled from block **N18**, the momentary voltage on terminal **M19** of the decoder circuits **134** is transferred to the same terminal in FIG. **15E**. This picks up relay **RM19** which seals in via its contacts **RM19***a* and normally closed contacts **RG01***d*, **RM70***d*; and it energizes a time delay device **TD9** which shortly thereafter energizes a differentiator **248** which produces a pulse on the terminal *g*,—to restart the tape reader **131**. When relay **RM19** picks up, its contacts **RM19***b* open to drop out relay **R14**; and the contacts **R14***b* open to deenergize relay RBD. The voltage at terminal *i*

is removed, and the reader **131** will not be affected by any delete codes DE contained in the tape **130**.

The reader **131** next reads block N**20** (and does not delete it). When the M**85** code is read and signaled, the solenoids RS and FS are energized to retract the probes **81** and **106** (see the above description of the M**85** Routine), and the reader **131** is restarted.

The reader next reads Z+003.000 from block N**21** into the Z storage device **140**, reads the G**51** code, reads the EOB code and stops. A G**51** Routine is now executed, and the wheel is moved, under control of data on the profile tape **120**, until it travels a distance of 3 inches to the right (i.e., from position **21**(**2**) to position **21**(**4**) in FIG. **7**). The right edge of the roll is now aligned with the right edge of the roll surface to be ground, but the wheel is not yet in contact with the roll surface. When this G**51** routine is completed, the tape reader **131** is restarted.

The next block N**22** results in the reading of an M**70** code and the execution of an M**70** Routine as described above. That is, the cross slide **40** is moved inwardly until the wheel just touches the roll, the slide is then stopped, and thereafter the tape reader is restarted. When the relay M**70** is picked up during this operation, the contacts RM**70***d* (FIG. **15**E) open to unseal relay RM**19**. The wheel is now ready to begin an infeed and grinding operation at the right end of the roll, as will be described later.

b. Left End Larger

On the other hand, if the left end of the roll **22** is the larger, then at the completion of the M**64** alignment routine, the relays R**14** and RBD will both be deenergized and a voltage to enable block delete operation will not be present on terminal *i* (FIGS. **15**E and **6**B). Therefore, when the tape reader begins reading block N**15** (see above) it will ignore the DE code therein, read the M**86** code, read the EOB code and stop. An M**86** Routine, as described above, will now be executed, resulting in the motor MRG driving the probe body until the probe signal E is reduced to zero. In this case, the voltage E will initially be negative, so the probe body will be driven inwardly toward the roll to a null condition. The tape reader **131** will then be restarted because relay R**8** picks up via current flow through contacts RM**61***h*, RG**55***c*, RM**86***d*, RM**87***d*, RM**84***e* and RM**85***d* (FIG. **15**D).

The tape reader **131** will then read block N**16** and an M**85** Routine (described above) will be executed to retract the probe from the roll surface.

The tape reader **131** will next read block N**17**, causing the number −149.000 to be stored in register **140** and the execution of a G**51** Routine (described above). The wheel **21** (still retracted from the roll) will move from the position shown at **21**(**1**) to that at **21**(**5**) in FIG. **7**. The wheel now has its left edge opposite the left edge of the roll surface to be ground, and the tape reader **131** is restarted.

The reader then reads block N**18**, causing a momentary voltage on terminal M**19** of the decoder circuits **134** and pick up of the relay RM**19** (FIG. **15**E) which seals in. The director **125** contains Z position sign signaling circuits which apply a voltage to its terminal *i* whenever the wheel **21** is on the left side of the roll center LC, i.e., when the Z position is negative relative to the Z zero or reference location. This terminal *i* connects as shown in FIG. **15**E, to a relay RL so that the latter will be energized when the wheel is to the "left" of center along the Z axis. At this time, therefore, the relay RL will be picked up and its contacts RL*a* closed. Thus, when relay RM**19** is picked up in response to reading of block N**18**, the closure of contacts RM**19***c* causes energization of the relay RBD. A voltage also appears on terminal *i*, so the reader **131** is conditioned to respond to any block delete codes DE which may be read from the tape. After the delay produced by device TD**9**, the tape reader is restarted.

Because the block delete operation is now enabled, the reader **131** will simply skip blocks N**20** and N**21** which contain DE codes. It will proceed to read block N**22**, causing execution of an M**70** Routine, so that the wheel (now at position **21**(**5**) in FIG. **7**) will be moved inwardly by the cross slide motor MC until it just touches the roll surface. As an incident to the M**70** Routine, the contacts RM**70***d* will open to drop out relay RM**19**, and the contacts RM**19***c* will open to drop out relay RBD. The tape reader **131** will then restart.

c. Status of the System Prior

to First Grinding Pass

From the foregoing, it will be understood that the wheel **21** has been brought into touching contact with the roll **22** at either the right or the left end of the roll surface, whichever is the larger in diameter. The probe **81** is retracted by its solenoid RS free of the roll surface. If the wheel is at the right end of the roll, the probe body is in a position such that a null signal would be produced if the probe were extended into engagement with the left gaging band *b***2** which is smaller in diameter than band *b***1** (the body having been set to that position during the roll axis alignment procedure, described above). On the other hand, if the wheel is at the left end of the roll, the probe body is in a position such that the probe signal would be a null if the probe were extended to engage the right gaging band *b***1**,—which is smaller in diameter than the band *b***2**. The probe body was set to this position by execution of an M**86** Routine in response to reading of block N**15**, as described above.

A rough grinding operation may now be started to remove metal from the roll surface, by passing of the wheel along the profile path, until the ends of the roll surface are reduced to the diameter of the smallest gaging band (the band *b***2** if the wheel is now at the right end of the roll, or the band *b***1** if the wheel is now at the left end of the roll). As a preliminary to actual grinding, however, the roll and wheel speeds, the contouring feed rate and the continuous infeed rate may be commanded to have desired values. By way of example, the next block of data on the sequence tape may contain:

N**23**
S**20**
W**50**
F**005**
C**20**
X−0.005
G**01**
EOB

When the S**20** code is read and signaled, the number "**20**" replaces the previous number "**24**" in the storage device **140**, so the headstock motor MH is now controlled to drive the roll **22** at 20 r.p.m. When the W**50** code is read, the number "**50**" replaces the number "**40**" in the storage device **144**, so the wheel motor MW is now controlled to drive the wheel at 500 r.p.m. When the F**005** code is read, the number "**5**" replaces the previous number "**120**" in the storage register **142**, so that the director **125** is conditioned to produce movement of the wheel along the profile at a feed rate of 5 inches per minute. When the code C**20** is read, the number "**20**" is stored in the register **145**, so voltage V*c* takes on a magnitude which represents a desired rate of continuous infeed of the wheel during grinding, this rate being selected to compensate for wear of the wheel at the chosen roll speed, wheel speed and feed rate.

Next, when the X−0.0005 data is read and signaled, the number −0.005 is stored in the register **141**. Then the G**01** code is read and signaled, and the EOB code is read to stop the reader **131**. The system now executes a G**01** Routine (described above) to feed the wheel into the roll a first X axis increment of 0.005 inch (at either the right or left end of the roll surface). The tape reader **131** then starts.

d. First Grinding Pass and Continuous Passing

The next block of the sequence tape calls for the execution of successive grinding passes of the wheel, with the wheel being fed inwardly a predetermined increment along the X axis at the end of each pass, and the wheel being fed continuously inward during passing to make up for wheel wear (such infeed being modified by the torque load on the wheel),—until the roll surface has been ground down at its ends to the diameter of the smallest gaging band. This next block may be:

N24
X–0.0004
Z+152.000
M72
G55
EOB

When the X command number is read, the value –0.0004 is stored in the register **141**. This produces no immediate effect, but represents the incremental X axis infeed to be given to the wheel at the end of each pass, as explained below.

When the Z command number is read, the value +152.000 is stored in the register **140**. The sign of the number is in this case not significant, and the storage of the number produces no immediate effect. The number represents the extent of motion along the Z axis during each grinding pass as explained below. It will be seen from the example of FIG. **7** that the wheel must travel 152 inch along the Z axis to move from the end position **21**(4) to position (**21**(5) or vice versa.

When the M**72** code is read and signaled by a voltage on the terminal M72 of the decoder circuits, such voltage results in pick-up of a relay RM**72** (FIG. **15**F) which seals in via contacts RM**72***a*, REP*c*, and RM**73***b*. Therefore, the contacts RM**72***b* (FIG. **15**D) close to supply the voltage Ec from FIG. **6**B to an input of the amplifier or controller **226** associated with the cross slide motor MC. Accordingly, the motor MC begins feeding the cross slide and the wheel inwardly toward the roll at a very slow rate, to compensate for the gradual reduction in wheel diameter due to wear. The rate of continuous infeed is determined by the magnitude of the voltage Ec and this in turn is determined by the algebraic sum of the voltage Vc and the voltage supplied from potentiometer wiper **162***a*. Thus, if the wheel feeds inwardly too fast and the torque load thereon increases, the voltage Ec is reduced and the rate of infeed decreased. The code M**72** may be considered as commanding the system to "start continuous infeed with load control."

G**55** Routine. When the G**55** code is read and signaled a "-continuous passing" operation is initiated. The appearance of a momentary voltage on the terminal G**55** (FIGS. **6**B and **15**E) causes energization of a relay RG**55** which seals in through its own contacts RG**55***a* and normally closed contacts R**16***b*. An enabling voltage therefore passes through normally closed contacts REP*b* and appears on the terminal *k* (FIGS. **15**E and **6**B). Such control voltage conditions the director **125** to start the tape reader **122**, read the profile tape **121**, and move the wheel **21** along the profile from its existing position through a distance (152 inches) then held in the Z storage register **140**. If the existing wheel position is positive (right), the motion is negative (left) along the Z axis; if the existing wheel position is negative (left), the motion is positive (right) along the Z axis. Thus, the wheel having been fed into the roll surface by 0.0005 inch at that end of the roll which is largest in diameter, the wheel is, in response to the G**55** command, moved along the profile to the other end of the roll while grinding metal from the latter. The bite of the wheel progressively decreases (if the roll is tapered) as this first grinding pass is executed. When the director **125** has moved the roll a distance of 152 inches (stored in the register **140**), it stops the contouring motion, and signals that the pass is complete by producing a voltage on its control terminal *ep*.

This latter voltage on terminal *ep* is fed through the now-closed contacts RG**55***b* (FIG. **15**E) to energize an "end pass" relay REP, which seals in via contacts REP*a*, R**16***c* and R**17***d*. This opens contacts REP*b* (FIG. **15**E) to remove the voltage from terminal *k*, so the director **125** is taken out of its profile pass mode. Also, contacts REP*c* open to deenergize relay RM**72** (FIG. **15**F) so that contacts RM**72***b* (FIG. **15**D) open to terminate the continuous infeed by the motor MC. Also, contacts REP*f* (FIG. **15**C) close to energize relay RM**84** which seals in via contacts RM**85***b* and opens its contacts RM**84***b* to deenergize solenoids RS and FS, so that the rear probe **81** is released to engage the roll surface.

The rear probe signal E now indicates whether or not the roll surface at the end being sensed has been reduced a predetermined amount, in this case to agreement with the surface of the smallest gaging band (upon which the rear probe was previously nulled). If the signal E (FIG. **12**) is finite and positive in polarity, such reduction has not been effected. But if the signal E is zero or negative in polarity, such reduction has occurred. In the former case, another grinding pass will be performed; in the latter case, the passing is terminated and the tape reader **131** is restarted.

i. Case I—Material Removal Incomplete

At the end of the first (or any other) grinding pass, the relay R+ will be energized by the polarity trigger **245** (FIG. **12**) if the probe signal E is finite and positive after the probe has been released to engage the roll surface at one end. Under these conditions, the contacts REP*d* (FIG. **15**F) will be closed because relay REP is energized at the end of any grinding pass; the contacts RM**84***f* will close when relay RM**84** is energized to release the rear probe **81**, as just described, so that a time delay device TD**8** will produce an output voltage at an instant shortly after the contacts RM**84***f* close; and the contacts R+*b* will be actuated and closed (with the contacts R+*c* open). Thus, a relay R**15** will be energized by current flow through normally closed contacts R**17***a*.

As a result, the contacts R**15***a* (FIG. **15**E) close to energize relay RG**01**, which seals in via contacts RG**01***a*, R**17***c*, and R**8***d*. The system now executes a G**01** Routine (as described above) and therefore the wheel **21** is moved along the X axis through the distance and direction represented by signals for the X storage register **141**. From reading of block N**24** (see above) this stored number is –0.0004. Therefore, the wheel is fed inward by an increment of 0.004 inch before the next grinding pass is begun. This is termed the incremental infeed. When such G**01** Routine is completed and the director produces a momentary voltage on its terminal *h*, the relay R**8** (FIG. **15**D) is not energized (and the tape reader **131** is not restarted) because the contacts RG**55***c* are open during execution of any G**55** Routine. However, the voltage at the same terminal *h* in FIG. **15**F does pass through the now-closed contacts RG**55***d*, and a relay R**17** is picked up. In consequence:

a. Contacts R**17***a* open momentarily to drop out relay R**15**.
b. Contacts R**17** *b* (FIG. **15**C) close momentarily to pick up relay RM**85**, so that RM**84** is deenergized and the probe **81** is retracted, as previously explained. The relay R**8** is not energized when contacts RM**85***e* close, because contacts RG**55***c* are now open. Relay RM**85** drops out when contacts RM**84***c* open.
c. Contacts R**17***c* (FIG. **15**E) open momentarily to drop out relay RG**01**.
d. Contacts R**17***d* open momentarily to drop out relay REP.
e. Contacts R**17***e* (FIG. **15**F) close momentarily to energize relay RM**72** which seals in via contacts RM**72***a*, REP*c* and RM**73***b*,—so that continuous infeed drive by the motor MC is restarted by closure of the contacts RM**72***b* in FIG. **15**D.

When relay REP is thus deenergized, its contacts REP*b* (FIG. **15**E) reclose, so a voltage is again applied to control terminal *k*, placing the director in a profile pass mode, and causing it to start the tape reader **122**. Thus, the director **125** again causes movement of the wheel **21** along the programmed contour from one end of the roll surface to the other. Since the wheel was infed by an increment of 0.0004 inch prior to this

second pass of the wheel, another small thickness of material will be removed from the roll surface, except of course at any worn or low spots.

So long as the relay R+ is energized at the end of any pass when the probe **81** is released to sense the roll, the sequence of operations just described will be repeated over and over. The wheel will be passed from one end of the roll to the other, the roll surface will be sensed by the probe assembly, the wheel will be given an X axis increment of infeed, and another pass will be started.

ii. Case II—Material Removal Complete

If, however, at the end of any grinding pass, the released probe **81** results in a signal E which is zero or negative, the relay R+ (FIG. **12**) will not be energized. The contacts R+*b* will be open and the contacts R+*c* (FIG. **15F**) will be closed when the device **TD8** produces an output voltage after closure of the contacts **RM84***f* when the probe **81** is released. Therefore, the relay **R16** instead of the relay **R15** will be energized. In consequence:

a. Contacts **R16***b* (FIG. **15E**) open to unseal relay **RG55**.
b. Contacts **R16***c* open to unseal relay REP. The contacts REP*b* close, but no voltage appears on terminal *k* because contacts **RG55***a* are open.
c. Contacts **R16***d* (FIG. **15C**) close to energize relay **RM85** which seals in, so that contacts **RM85***b* open to drop out relay **RM84**, thereby closing contacts **RM84***b* to energize solenoids RS, FS to retract the probes. The relay **RM85** then drops out.
d. As an incident to pickup of relay **RM85**, its contacts **RM85***d* (FIG. **15D**) open substantially simultaneously with reclosure of the contacts **RG55***c*. However, the contacts **RM85***e* close, so that after a delay measured off by a device **TD5***a*, the relay **R8** picks up momentarily. This closes the contacts **R8***a* and after a delay created by device **TD5**, a voltage pulse appears on the terminal *g*, thereby restarting the tape reader **131** (FIG. **6B**).
e. When relay REP drops out, its contacts REP*d* (FIG. **15F**) open to deenergize relay **R16**, but the latter does not restore its contacts to a deactuated state until relay **RG55** has been deenergized and relay **RM85** has picked up.

In summary, the first pass of the grinding wheel in contact with the roll surface has been started from that end of the roll which has the largest diameter. Passes were then automatically and repeatedly executed, with incremental infeed after each one, until the rear probe assembly signaled a predetermined or first value, i.e., a zero or positive voltage, at the end of the last pass. In this instance, such signaling occurred when the roll surface at one end became equal to or less in diameter than the smallest diameter gaging band. Thus, the gaging bands have been "ground off."

5. Rough Grinding

From experience with a number of worn rolls from a given mill, or from inspection of any particular roll, the programmer who makes up the sequence tape will know about how much metal must be removed from the roll surface to eliminate low, worn spots and surface irregularities. The major portion of the metal to be removed may be taken off by rapid, rough grinding, which leaves a poor surface finish. The final portion may be removed with different infeeds and wheel speeds to yield a good surface finish. The surface may then be "sparked" for better finish and then "polished" by operating the wheel with different speed or feed parameters.

In accordance with the invention, a predetermined amount of material is removed from the surface of the workpiece by the presetting a roll surface sensing means (here the probe assembly **80**) and executing grinding passes automatically until it is determined at the end of any given pass that the roll surface has been reduced by the amount of the preset.

The rough grinding operation is begun when the **G55** routine is completed and the tape reader **131** is restarted as described above. By way of example, the next block on the sequence tape **130** may contain:

N25
U—0.0090
G00
E0B

The command U—0.0090 designates that rough grinding is to proceed until the radius of the roll has been reduced by 0.009 inch. That is, the diameter is to be reduced by 0.018 **inch.** When this U command is read and signaled, the number 0.0090 is stored in the register **147** (FIG. **6B**) and represented on its output conductors. The code **G00** is then read and signaled, and reading of the **E0B** code stops the tape reader **131**.

The momentary voltage which appears on the terminal **G00** (FIGS. **6B** and **15F**) immediately picks up a relay **RG00** which seals in via contacts **RG00***a* and **R18***a*. The voltage on terminal **G00** also causes a differentiator **250** to produce a pulse on terminal *y* (FIGS. **15F** and **11**) which opens preset gates **186** so that the number (here 0090) then signaled by the U storage device **147** (FIG. **6B**) is preset into the rear probe assembly counter **170**. And, after a delay measured off by time delay device **TD10**, a relay **R19** also picks up.

Actuation of the relay **RG00** closes the contacts **RG00***b* (FIG. **15B**) to apply a positive input voltage to the driver **211** so that motor MRG is energized to step the probe body **88** (FIG. **4**) inwardly. It will be recalled that at the end of the **G55** Routine described above, the probe **81** had been engaged with one end of the roll surface and nulled, and the probe was then retracted.

As the motor MRG steps the probe body inwardly, pulses from the feedback generator Pr (FIG. **11**) are applied by the pulser **184** to the "down" input of the counter **170**. When the counter counts down to zero from the number (0090) previously set therein, a zero decoder **252** connected to the counter output conductors produces a voltage signal EQ. The latter signal passes through the now closed contacts **R19***a* (FIG. **15F**) to energize a relay **R18**. The contacts **R18***a* open to deenergize relays **RG00** and **R19**, so contacts **RG00***b* in FIG. **15B** open to stop the rear gage step motor MRG. The probe body has thus been moved inwardly toward the roll by a distance of 0.009 inch from a previous null position. When the relay **R18** picks up, the immediate drop out of relay **R19** and opening of contacts **R19***a* again deenergizes relay **R18**. But a momentary voltage pulse appears on the terminal *g*, and serves to restart the tape reader **131**. The probe body **88** at this time has been set to a position such that with the probe engaged with one end of the roll surface, the probe signal E has a first value or magnitude indicative of the thickness of material (0.009 inch) to be removed.

The next block on the sequence tape may contain the operating parameters for rough grinding and the magnitude for incremental infeeds. For example it may include:

N26
S18
W45
F060
C40
X—0.0009
G01
E0B

The block **N26** is similar to block **N23** treated above, and the responses to reading of the codes will be the same as there described in detail. It will suffice to note that reading of the codes **S18**, **W45** results in the roll **22** and wheel **21** being driven at speeds of **18** and 450 r.p.m., respectively. Reading of the code **F060** conditions the director **125** to move the wheel at a feed rate of 60 inches per minute along the profile path. Reading of the code **C40** conditions the controls for motor MC such that the continuous infeed will be faster to compensate for the more rapid wear of the wheel **21** during rough grinding. Reading of the X command stores the number —0.0009 in the register **141** and reading of the code **G01**

causes execution of a G01 Routine to give the wheel 21 an initial incremental infeed of 0.0009 inch into the surface of the roll.

The tape reader 131 is then restarted and it reeds the next block which contains:

N27
X–0.0009
Z+152.000
G55
M72
E0B

This data block N27 is similar to the block N24 treated above. The response to reading of block N27 need not be repeated in detail, and reference may be made to the foregoing description of the G55 Routine. It may be noted simply that the director will now start moving the wheel 21 through successive grinding passes with continuous infeed. At the end of each pass, the probe 81 will be released to sense the roll surface. If the probe signal is still positive, the wheel will be incrementally infed by 0.0009 inch and another pass initiated. If the probe signal is zero or negative, the passing will be terminated, and the tape reader 131 restarted. Noteworthy is the fact that the diameter of the wheel 21 or the wear thereon are relatively immaterial. Passing will continue until the desired thickness (0.0090 inch, the programmed U number in block N25) of material has been removed from the roll surface.

6. Finish Grinding

When rough grinding passes have been completed, the tape reader 131 starts to read the next block:

N28
U–0.0010
G00
EOB

The response to reading of this block is the same as that described above for block N25, except that the probe body will be set inwardly by only 0.001 inch inasmuch as less material is to be removed from the roll during final grinding.

The tape reader 131 will then start and read the next block on the sequence tape:

N29
S30
W60
F030
C10
X–0.0001 inch
G01
EOB

This block N29 sets up the operating conditions for finish grinding. Reading of this block produces the same operations as described in details for blocks N23 and N26. However, for finish grinding the roll speed will be 30 r.p.m., the wheel speed will be 600 r.p.m., the contouring feed rate will be 30 in./min., and the continuous infeed rate (C10) will be markedly lower than before, because wheel wear will be at a lesser rate. The wheel 21 will be given an initial infeed increment of 0.0001 inch so that it will take a very slight bite on the first pass of the finish grinding operation.

Next, the tape reader reads the following block on the sequence tape.

N30
X–0.0001
Z+152.000
G55
M72
E0B

The response to the reading of these data is similar to that described above for block N24, except that the incremental infeed at the end of each grinding pass will be only 0.0001 inch. Passes will be repeatedly executed until 0.0010 inch (the U command of block N28) of material has been removed. The tape reader 131 will then be restarted. At this time the probe 81 has been retracted and the continuous infeed has been stopped. The wheel 21 is disposed at one end or the other of the roll surface.

7. Sensing and Signaling the Roll Diameter

After the finish grinding, it is desirable to sense and signal the diameter of the roll at a predetermined axial location, since that information may be required when the roll is returned to service in a mill. Also, if a second roll is to be ground with a matching diameter, as described below, the diameter of the first roll should be determined by the measuring instrumentalities associated with the machine.

After finish grinding, the reader reads the next block which contains:

N31
X+0.0100
G01
E0B

These date call for the wheel 21 to be retracted free of the roll surface by a predetermined distance, so that the wheel may be moved lengthwise of the roll without touching the latter. The reading of block N31 results in the execution of a G01 Routine, as described above, with the wheel thus being moved outwardly 0.01 inch and at a feed rate of 30 inch/min. (F030 having been stored in register 142 from reading of block N29). The next block of sequence command data is then read and contains:

N31*a*
P4
G04
M83
M82
E0B

When the P4 code is read and stored in the register 146, it conditions the dwell timer 225 (FIG. 15C) to measure off a long time interval. The reading of the G04 code puts the system in a dwell mode so that the tape reader 131 will not be restarted (as described above for a G04 Routing) until the other commanded functions have been completed.

The codes M83, M82 and E0B are read and signaled, and the reader 131 stops. The momentary voltages appearing on the terminals M83 and M82 (FIGS. 6B and 15B) result in pickup of the relays RM83 and RM82. Relay RM83 seals in through its contacts RM83*a* and the normally closed contacts LSRG*a* of the limit switch LSRG associated with the rear probe assembly (FIG. 4). Relay RM82 seals in through its contacts RM82*a* and the normally closed contacts LSFG*a* of the limit switch LSFG associated with the front probe assembly 106. The contacts RM83*b* close to apply a negative voltage to the step driver 211 and the motor MRG thus drives the rear probe body away from the roll until limit switch LSRG is actuated to drop out relay RM83. Similarly, the contacts RM82*b* close to apply a negative voltage to driver 204 (FIG. 15C), so the motor MFG retracts the front probe body until limit switch LSFG is actuated and relay RM82 drops out.

When the probe bodies have been fully retracted, the contacts LSRG*b* and LSFG*b* (FIG. 15B) will both close, causing differentiators 260 and 261 to produce voltage pulses on terminals *p* and *q*, respectively. These terminals appear in FIG. 11, and the enabling voltages thereon open the gates 188 and 190, so that the number 33.000 is preset into both of the counters 170 and 171. Summarized, the reading of M83 and M82 codes results in the rear and front probe bodies being fully retracted, and the front and rear probe counters 170, 171 being preset to hold predetermined numbers (here, 33.000).

Referring to FIG. 3, the probe body 88 is there shown by solid lines in its fully retracted position, and by dotted lines advanced such that the probe 81 is engaged with the surface of the roll 22. For any given grinding machine, the distance between the center of the machine C*m* and the tip of probe 81 (solid lines) when (a) the body is fully retracted and (b) the probe shifted into the body to a null position, is a predeter-

mined and known quantity, here labeled and assumed to be 33.000 inches (hereafter referred to simply as 33 inches). If the roll **22** is placed in the machine with its cross-sectional center C*r* coincident with the machine center C*m*, then it would be possible to determine and numerically signal the roll diameter by using the rear probe assembly alone. The probe body **88** would be fully retracted and the rear probe **170** preset to contain the number **33**, as described above. Then the rear probe body would be advanced until a null signal is obtained, while pulses from the feedback generator P*r* were counted down in the counter. The counter would then hold a number representing the roll radius **R1**, and by doubling that number, the diameter **D1** of the roll would be obtained.

However, it may often happen that the roll **22** is placed in the grinding machine with its center C*r* displaced from the machine center C*m*, as shown in FIG. **3**. There is no certainty that the two centers will coincide. A diameter determination by use of the rear probe assembly along would be inaccurate because the extent of the displacement of the centers C*m* and C*r* is unknown.

To determine and signal the diameter of any roll **22**, therefore, the front and rear probe assemblies are both utilized, since they collectively form a caliper structure capable of determining the spacing between the front and rear surfaces of the roll, and thus the diameter **D1**. The procedure will become clear as the following description proceeds, bearing in mind that the probe bodies **88** and **110** have first been fully retracted and their associated counters set to hold the number 33.000. The distances from the center C*m* to each probe tip when its body is fully retracted and the probe is in a null position is known, and in the present example is assumed to be 33 inch. If now the two probe bodies are advanced toward the roll until their probes are deflected by the roll surface to null positions, and if during such advancement, feedback pulses from the generators P*r* and P*z* are counted downwardly in the counters **170** and **171**, then the two counters will end up containing numbers representing the distances *m* and *n*. By adding the numbers *m* and *n* the diameter **D1** is obtained. And by dividing the diameter **D1** by two, the radius **R1** is obtained.

After the commands of block **N31***a* have been executed and dwell timer **125** completes the **G04** delay (as described above), the next block on the sequence tape **130** is read, and it contains:

N32
M19
E0B

Accordingly, the relay **RM19** (FIG. **15E**) is energized and sealed in via its contacts **RM19***a* and normally closed contacts **RM70***d*. At this time the wheel **21** is at either the right or left end of the roll surface, the relay RL in FIG. **15E** will be deenergized or energized, and the contacts RL*a* in FIG. **15E** will be open or closed, respectively. Therefore, when relay contacts **RM19***c* close, the relay RBD will be left deenergized or will be energized, depending upon whether the wheel **21** (after completion of the finish grinding) is at the right or left end of the roll surface. If it is at the left, a block delete enabling voltage will appear on the control terminal *i*. After an interval measured off by the delay device **TD9**, the differentiator **248** will apply a pulse to the terminal *g*, and the tape reader **131** will be restarted.

The next block of data read from the tape contains commands to move the wheel **21** from the right to the left end of the roll, providing it is not already at the left end. This next block has the data:

N33
DE
F120
Z−152.000
G51
E0B

When the delete code **DE** is read, the rest of the block is ignored, and the reader **131** proceeds to read the next block, if an enabling signal is present on reader control terminal *i* because the wheel is at the left end of the roll. But if the wheel is at the right end of the roll, the remainder of the block is read. It will be recognized from what has been said above that the reading of the code **F120** conditions the director **125** to move the wheel along the profile path at a feed rate of 120 inches/min. Also the reading of the Z number and the **G51** code results in execution of a **G51** Routine (as described above), so that the profile tape **121** is read and the wheel **21** (now retracted free of the roll) is moved from the right to the left end of the roll, i.e., from the position **21(4)** to position **21(5)** shown in FIG. **7**. The tape reader **131** is then restarted.

The purpose of blocks **N32** and **N33** is to place the wheel **21** (and thus the probe **81**) at a predetermined axial location where the roll diameter is to be measured, such location in the present instance being that at which the wheel is opposite the left end of the roll surface. One might, as a matter of preference, choose the lengthwise center of the roll, or the right end as the predetermined axial location.

The next block on the sequence tape includes:

N34
M86
E0B

Reading of these data causes execution of an **M86** Routine, as to which reference may be made to the operations described above. Summarily stated, the probes **81, 112** are released, the rear probe body **88** is driven inwardly until the probe engages the roll surface and is deflected to a null position, and the tape reader **131** is then restarted when relay **R8** is energized by closure of contacts **RM86***d* (the contacts **RM84***e* having been closed previously when relay **RM86** picked up) when relay **RM86** drops out.

While the probe body **88** is thus driven inwardly to the position shown by dotted lines in FIG. **3**, pulses from the generator P*r* are counted downwardly in the counter **170** (FIG. **11**). Since the counter started with the number 33.0000 set therein, it ends up containing that number less the distance the probe body moved, and thus it contains and digitally signals a number representing the distance *m* shown in FIG. **3**.

The next block read from the sequence tape is:

N35
M85
E0B

This results simply in retraction of the probes **81** and **112**, as previously explained for an **M85** Routine, and the tape reader **131** is then restarted.

As shown in FIG. **6A**, the front probe **112** is offset by a predetermined distance (30 inches) to the left of the rear probe **81**. To bring the front probe **112** to the same axial location previously sensed by the rear probe, the carriage **42** is next moved 30 inches to the right. For this purpose, the next block contains the commands:

N36
F120
Z+30.000
G51
E0B

The reading of the **F120** code conditions the director **125** to produce a feed rate of 120 inches/min. (if it was not already so conditioned). Then, a **G51** Routine, as previously described, is executed to cause the wheel **21** to follow the profile until it has moved 30 inches to the right. The probe **112** is now opposite the left end of the roll surface, specifically 2 inches in from the left end, and at the same axial location previously occupied by the probe **81**. The tape reader **131** is restarted.

The next block contains the command:

N37
M87
E0B

When the **M87** code is read and signaled by a momentary voltage on the terminal **M87** (FIGS. **6B** and **15B**) a relay **RM87** picks up and seals in through its contacts **RM87***a* and the normally closed contacts **RZF***b*. Thus, contacts **RM87***d* (FIG. **15D**) open so that relay **R8** will not be energized until they

reclose after contacts RM84*e* subsequently close. The contacts RM87*b* (FIG. 15C) close to energize the relay RM84 which seals in via RM84*a* and RM85*b*. As a result contacts RM84*b* open to deenergize RS, FS and thus to release the probes. Contacts RM87*c* close to apply a positive voltage to the pulse driver **204**, so that the motor MFG is energized to step the front probe body (FIG. 4) inwardly toward the probe **22**. When the probe **112** engages the roll surface and is shifted to a null position, the voltage E*f* (FIG. **13**) is reduced to zero, and the zero detector **119** thereupon energizes the relay RZF. This results in opening of the normally closed contacts RFZ*b* in FIG. 15B to drop out the relay RM87. Therefore, the contacts RM87*c* open to stop the motor MFG; and contacts RM87*d* in FIG. 15D reclose so that the relay R8 is energized through the now-closed contacts RM84*e* and the normally closed contacts RM85*d*. The relay contacts R8*a* close and thus produce a momentary voltage on terminal *g* which starts the sequence tape reader **131**. While the probe body **110** was thus driven inwardly to the positions shown by dotted lines shown in FIG. 3, pulses from the generator P*f* were counted downwardly in the counter **171** (FIG. **11**). Since the counter started with the number 33.000 set therein, it ends up containing that number less the distance the probe body moved, and thus it contains and digitally signals a number representing the distance *n* shown in FIG. 3.

The next block read from the sequence tape is:

N38
M85
E0B

This results simply in retraction of the probes **81** and **112** by their respective solenoids RS and FS, as previously explained for an M85 Routine, and the tape reader **131** is then restarted. The counters **170** and **171** in FIG. **11** now digitally signal the numbers *m* and *n*. To cause the sum of these numbers to be computed and printed out or displayed, the next block of the sequence tape contains an M80 command. The block may be simply:

N39
M80
E0B

When the code M80 is read and signaled by a momentary voltage on the terminal M80 (FIGS. 6B and 15G), a relay RM80 picks up and seals in via its contacts RM80*a* and normally closed contacts R20*a*. The positive voltage thus applied to a differentiator **265** results in the latter producing a voltage pulse on a control terminal *r* connected to the computer **165** in FIG. **10**, thereby conditioning the computer to add the two numbers subsequently applied to its input bus IB. This same positive voltage is applied to the input of a time delay device TD11 so that after a time interval, a differentiator **266** is energized to produce a momentary voltage on the control terminal *o*. This voltage appears on the terminal *o* in FIG. **11**, momentarily opening the readout gates **172** so that the number *m* then held in the counter **170** is signaled on the input bus IB of the computer **165**.

The output of the device TD11 formed an input signal to another time delay device TD12 so that after another time interval a differentiator **267** produces a momentary voltage pulse on the control terminal *o*1. This voltage appears on the correspondingly labeled terminal in FIG. **11** to open the readout gates **173**, thereby applying the number *n* signaled by the counter **171** to the input bus IB. The computer **165** in FIG. **10** thus signals this sum of the numbers *m* and *n* on its output bus OB.

The output voltage from the time delay device TD12 (FIG. 15G) is applied to the input of another time delay circuit TD13, so that after an interval a differentiator **268** supplied a voltage pulse through normally closed contacts RM89*b* to a control terminal *s*. This momentary voltage appearing on the same terminal in FIG. **10** enables the printout device **175** so that the latter prints out and records, or visually displays, the number then signaled on the output bus OB. As will become apparent the number thus printed out represents the diameter D1 of the roll **22**, as shown in FIG. 3.

The output voltage from the time delay device TD13 is also connected to energize a relay R20 (FIG. 15G), so that once the printout operation has been initiated (and will proceed to completion) by the signal on control terminal *s*, the relay R20 is actuated. Its normally closed contacts R20*a* open to break the holding circuit for relay RM80 and also to remove the input voltages applied to the devices TD11, TD12, TD13. This deenergizes the relay R20 very shortly after it is picked up. But during the short time that relay R20 is picked up, its contacts R20*b* are closed to apply a voltage pulse to the control terminal *g* and which thus causes restarting of the sequence tape reader **131**.

Referring to FIG. 3, where the total spacing between the probe tips as shown in solid lines (i.e., with the bodies **88**, **110** fully retracted and the probes nulled) is represented by a number K (here, 66 inches), then the distance from each probe tip to the machine center C*m* under these conditions is K/2 (here, 33 inches). The probe tips with the bodies **88** and **110** fully retracted and the probes positioned at null in the bodies lie on two respective reference lines parallel to the Z axis and spaced apart by the distance K. As the probe bodies **88** and **110** are then moved inwardly, the generator P*r* and P*f* measure off and signal the distances *d*1 and *d*2 through which the bodies move to null the probes in contact with the roll surface. The distances *m* and *n* are thus expressed:

$$m = K/2 - d1 \quad (18)$$

$$n = K/2 - d2 \quad (19)$$

Since the number *K*/2 (here, 33.0000) was first preset into the counters **170** and **171** and the numbers *d*1 and *d*2 are subtracted therefrom by pulses from the generators P*r* and P*f*, the counters end up containing and signaling the numbers *m* and *n*, respectively. The computer **165** is then caused to add these numbers, producing signals representing the diameter D1 of the roll, where

$$D1 = m + n \quad (20)$$

This is the number printed out by the device **175** in FIG. **10**.

Viewed in another sense, the number D1 is derived and signaled by assuming that the tips of the probes **81** and **112** define reference lines parallel to the Z axis and spaced from one another by a distance K (here, 66 inches). When the probe bodies **88** and **110** are moved in from their fully retracted positions to null the probes in contact with the roll, they move through distances *d*1 and *d*2, registered negatively in the counters **170**, **171** which have both originally been set to hold the number 33 inches, or collectively to hold number 66 inches. Therefore, the diameter D1 is expressible:

$$D1 = K - (d1 + d2) = m + n \quad (202)$$

In other words, the probe assemblies by the pulse generators therein measure off the spacings from two reference lines of known separation *K* to the respective, diametrically opposite points on the roll surface, and from this the diameter *D*1 is determined and printed out.

8. Cleaning Up the Roll Surface by Sparking Passes

Following the printout of the roll diameter, it is desirable to clean up the roll surface by "sparking" and "polishing" operations. These do not involve any incremental infeed at the end of each pass; they do not change the roll diameter, but merely improve surface finish. The diameter was measured, as described above, prior to these operations in order that engagement of the probes with the roll do not mar the finally finished surface.

At the end of the diameter printout operation, the wheel **21** is located 30 inches to the right from the left end of the roll surface and is retracted by a distance of 0.01 inch from that surface, and the probes **81** and **110** have been retracted into their bodies. The tape reader **131** begins to read the next block of the sequence tape, which contains:

N40
Z–030.000
G51
E0B

From the foregoing descriptions of operations performed during a G51 Routine, it will be understood that the reading of the foregoing commands results in the wheel 21 being moved to the left under the control of the director 25 and tape 121 along the profile path until the wheel is axially opposite the left end of the roll, as indicated by the position 21(5) in FIG. 7. The tape reader 131 is then restarted.

The next block on the tape contains command data to bring the wheel into touching engagement with the roll surface. These data are:

N41
F005
X–0.0100
G01
E0B

Reference may be made to the previous detailed description of G01 Routine operations which occur in response to the reading and signaling of a G01 code. Briefly stated, the wheel will move inwardly along the X axis a distance of 0.01 inch so that it is returned to the same X axis position which it occupied after completion of finish grinding and prior to the retraction of 0.01 inch effected in response to block N31, described above. The sequence tape reader 130 is restarted.

As an incident to execution of the G01 Routine, the relay RG01 is actuated, and its contacts RG01*d* (FIG. 15E) open, thereby deenergizing the previously sealed-in relay RM19. The contacts RM19*c* open and drop out the relay RB*d*. Thus, the voltage previously present on the terminal *i* is removed, and the tape reader 131 will no longer be responsive to the reading of a block delete code DE.

With the wheel barely in touching contact at the left end of the roll surface, the next block of data read from the sequence tape contains commands for speeds and feeds appropriate for "spark out" grinding passes. As indicated above, each such grinding pass will be taken without incremental infeed, and the continuous infeed will be at a very low rate since wear on the wheel will be slight. This next block on the sequence tape contains the following:

N42
S20
W60
F050
C05
Z+152.000
G51
M74
E0B

The reading of the S20, W60, F100 and C05 codes results (in the manner previously explained) with the storage of new numbers in the registers 143, 144, 142 and 145 (FIG. 6B). Thus, the headstock motor MH. will now be controlled to drive the roll 22 at 20 r.p.m. The wheel motor MW will not be controlled to drive the wheel at 600 r.p.m. The director 125 is conditioned so that the wheel will be moved along the contour path at a feed rate of 50 inches per minute when contouring motion is in progress. The voltage Vc will not be relatively small in magnitude, so that the speed of the motor MC for infeeding will be very small, thereby to compensate for the very slight rate of wear on the wheel during sparkout passes.

When the Z increment command and the G51 code are read and signaled from block N42, the system will begin executing a G51 Routine. The details of this routine have been described above, and it will suffice to observe simply that the wheel 21 is now moved in contact with the roll along the profile path defined by data on the tape 121 until it has moved to the right through a distance of 152 inches and thus is located at the right end of the roll, in the position 21(4) shown in FIG. 7. The tape reader 131 will then be restarted.

Immediately after the G51 code is read, and just as execution of the G51 Routine begins, the tape reader 131 will read and signal the M74 code, producing a momentary voltage pulse on the terminal M74 (FIGS. 6B and 15F). Thus, the relay RM74 will pick up and seal in through its own contacts RM74*a* and the normally closed contacts RM73*a*. As a result, the contacts RM74*c* (FIG. 6B) open to disconnect the potentiometer wiper 162*a* from the input to the amplifier 161. Also, the contacts RM74*b* (FIG. 15F) close to energize the relay RM72, so that contacts RM72*b* (FIG. 15D) close to connect the output voltage Ec from amplifier 161 to the input of the motor controller or amplifier 226. Thus, when the sparkout pass called for by the date in block N42 is initiated, the motor MC is energized to drive the cross slide 42 slowly in, i.e., to provide a small continuous infeed. This infeed takes place, however, without any "load control." That is, it is independent of torque loads imposed on the wheel motor MW.

When the sparkout pass called for by block N42 is completed, the tape reader 131 will be restarted to read the next block of data, which may contain simply

N43
Z–152.000
G51
E0B

The reading of these data will cause the execution of a G51 Routine, as described above, so that the wheel 21 will be moved from the right end to the left end of the roll surface, with very slight continuous infeed and so that surface irregularities are removed. The tape reader will then be restarted. Any number of sparkout grinding passes may be called for by a corresponding number of command blocks on the sequence tape. In the present instance, it will be assumed that a third sparkout pass is desired. Accordingly, the next block read in the reader 131 may contain:

N44
Z+152.000
G51
E0B

Again, the reading of the foregoing command data will cause the execution of a G51 Routine and the wheel 21 will be moved in contact with the roll surface along the profile until it reaches the right end of the roll. The tape reader 131 will then be restarted.

9. Polishing Passes

To finally polish the roll surface, the wheel 21 is passed one or more times in contact with the roll surface, but with no continuous infeed at all, and with wheel and roll speeds, and a feed rate, which result in a very smooth, mirrorlike surface finish. The next block on the sequence tape thus may contain, by way of example:

N45
M73
S24
W62
F080
z–152.000
G51
E0B

When the M73 code is read and signaled on the terminal M73 (FIGS. 6B and 15F), the relay RM73 is momentarily energized. Accordingly, the contacts RM73*b* open to break the holding circuit for relay RM72 so that the contacts RM72*b* in FIG. 15D open, thus stopping the motor MC and terminating the continuous infeed. Also, the contacts RM73*a* in FIG. 15F open momentarily to drop out the relay RM74.

The reading of the codes S24, W62, and F080 results in the storage of new numbers in the registers 143, 144 and 142 (FIG. 6B). As explained above, the motors MH and MW are now controlled to drive the roll 22 and the wheel 21 at speeds of 24 and 620 r.p.m., respectively. Also the director 125 is conditioned so that movement of the wheel along the contour path will occur at a feed rate of 80 inches per minute.

The reading of the Z command and G51 code from block N45 will result in the performance of a G51 Routine. From the descriptions given above, it will be understood that the director 125 will cause reading of the profile tape 121 and

movement of the wheel along the profile until it leaves the left end of the roll surface. The tape reader **131** will then be restarted.

Second and third polishing passes may be produced by execution of the commands contained in the next two blocks

```
N46
Z+152.000
G51
E0B

N47
Z−152.000
G51
E0B
```

The commands of blocks **N46** and **N47** are executed as **G51** Routines, as previously described. The wheel **21** thus moves along the profile in light contact with the roll surface (but with no incremental or continuous infeed) from the left to the right end of the roll, and then from the right to the left end. This concludes the polishing operation, and the tape reader **131** is restarted when the **G51** Routine of block **N47** has been completed.

The reader **131** then reads the next block from the tape **130**, which contains:

```
N48
P4
G04
M02
E0B
```

When the **P3** and **G04** codes are read and signaled, the relay RG04 (FIG. 15C) is picked up and the dwell timer **225** is started on a timing cycle which will end with the energization of the relay **R9**, as hereinbefore described. The contacts RG04*d* in FIG. 15A are thus closed in the holding circuit for relay **R1**, the holding circuit having been previously established through the normally closed contacts RM02e. During the interval measured off by the timing cycle of the dwell timer **225**, the code **M02** will be read and signaled, and the tape reader then stopped in response to the reading of the code **E0B**.

The code **M02** represents a command to stop the system. When this is read and signaled by a momentary voltage on the terminal **M02** (FIGS. **6B** and **15G**), a relay **RM02** will pick up and seal in via its contacts RM02*a*. The other contacts of this relay produce the following action

1. Contacts RM02*b* and RM02*c* in FIG. 15B close to pick up relays **RM82** and **RM83**. Thus, **M82** and **M83** routines, as previously described, are executed. The front and rear probe bodies **110** and **88** will be driven by their corresponding step motors to fully retracted positions, as described above with reference to block **N31**.
2. The contacts RM02*d* in FIG. 15D close to energize the relay **RM71**. Thus, an **M71** Routine will be executed. That is, the cross slide **82** will be driven by the motor MC to a fully retracted position and then stopped.
3. Contacts RM02*e* in FIG. 15A will open, but the holding circuit for relay **R1** remains complete because the contacts RG04*d* are now closed.

When dwell timer **225** (FIG. 15C) times out, its output voltage cannot reach the terminal *g* because contacts RM02g are now open. But relay **R9** is energized so its contacts R9*a* open to drop out relay **RG04**. Thus, the contacts RG04*d* in FIG. 15A open to break the holding circuit for relay **R1**. The contacts R1*b* and R1*c* thereupon open to remove the supply voltages from lines **L1** and **L3**. All relays in FIGS. **15A–E** are deenergized. Thus, relays **RM04** and **RM17** open contacts RM04*b* and RM17*b* (FIG. 6B) so that the motors MH and MW are stopped. The operation of the system is thus terminated with the front and rear probe bodies retracted free of the roll, the cross slide **40** retracted so that the wheel **21** is free of the roll, and all motors stopped. The roll **22** may now be removed from the grinding machine.

E. Grinding a Second Roll to the Same Diameter

It is often desirable to grind two rolls of a matched pair such that they will have the same crown or contour and the same diameters at corresponding axial locations. This may be accomplished conveniently without time-consuming manual measurements and with exact matching diameters because any errors which might possibly be introduced by the measuring means occur for both the first and second rolls of the pair and thus cancel one another. That one of the rolls which is the most worn or irregular is first placed in the grinding machine, and is reground under control of appropriate profile and sequence programs stored on the tapes **121** and **130**, in the manner fully described above. As a part of that procedure, the diameter **D1** at a predetermined axial location, namely, the left end of the first roll surface (more specifically, 2 inches to the right of the left end of such surface) is measured and printed out.

When the second one of the matched pair of rolls is to be ground, it is placed in the grinding machine and the same profile tape **120** employed in the grinding of the first roll is placed in the tape reader **121**. A different sequence tape **130**, made up for the second roll, is placed in the tape reader **131**. Then, as a part of the setup procedures, the diameter **D1** of the first roll (and which is now known because it was previously printed out) is fed into the system manually, that is, by setting manual digit switches or by typing it on a coding typewriter **131***a* which has coding means and output conductors leading to the input of the decoder circuits **134**. Thus, the diameter **D1** is represented by successive input signals D*xx.xxxx* to the decoding circuits, and this number is therefore routed to and stored in the storage device **148** whose output conductors thereby carry signals representing the first roll diameter **D1**.

The setup procedure for the second roll will be the same as that described above for the first roll. Also, the sequence tape **131** for the second roll may be identical for that of the first roll up through block **N23** (see foregoing description of Blocks NO1–N23). Thus, the sequence tape for the second roll will be read through the first 23 blocks thereon and the same operations performed as described above for blocks **N1** through **N23** in the case of the first roll. In this way, the control system will (1) locate the lengthwise center of the second roll and set the system to a zero reference condition, (2) align the second roll axis with the machine axis, and (3) determine the direction of the first grinding pass and grind the second roll surface to remove the gaging bands. At this point, the total amount of material to be removed from the surface of the second rolls depends not upon the depth of its worn spots or irregularities, but rather upon the difference between the existing diameter **D2** of the second roll and the finished diameter **D1** of the first roll.

For convenience in distinguishing blocks of data which appear on the sequence tape described above for a first roll, the block numbers for the second roll sequence tape will herein be designated with a prime symbol. The prime symbols are merely an aid to the present description and are not actually represented on the second roll sequence tape.

Following the block **N23'** on the sequence tape **131** for the second roll, the succeeding blocks **N24'**, **N24***a'* through **N31'** will be identical to the blocks **N31**, **N31***a* through **N38** described above with reference to the first sequence tape. These blocks **N24'** through **N31'** will thus be read to perform upon the second roll the same operations described above for blocks **N31** through **N38**. In other words, the numbers *m* and *n* (See FIG. 3) for the second roll are registered in and signaled by the counters **170** and **171** (FIG. 11) after the commands of block **N31'** have been executed.

It will be recalled from the previous description of blocks N31 through N38 that following the execution of the command in block n31' (which is identical to block N38), the wheel 21 and the rear probe 81 are located axially 30 inches to the right of the left end of the roll surface. The wheel is at this time slightly retracted from the roll surface, and the solenoids RS and FS are energized so that the probes 81 and 112 are retracted into their respective bodies 88 and 110. The two probe bodies have been located, however, such that if their probes were released opposite a point two inches to the right of the left end of the roll surface, then the probe assembly signals E and E*f* would be zero or null. When the tape reader restarts after execution of the block N31' (the numbers *m* and *n* now being signaled on the outputs of the counters 170 and 171) it reads the following block of data from the second roll sequence tape

N32'
U.001
M89
E0B

The U command number 0.001 designates the thickness of material which is to be removed during the finish grinding operations on the second roll. Thus, this number is simply routed into and stored by the storage device 147 in FIG. 6B, and is signaled on the output conductors thereof. The code M89 commands the system to advance the rear probe body by an amount equal to the thickness of material which must be removed from the second roll during rough grinding. That is, the rear probe body is moved inwardly (prior to rough grinding passes) by a distance which is equal to half the difference between the diameters D2 and D1 less the commanded thickness of stock to be removed during finish grinding. The symbols ΔRr and ΔRf will be used herein to designate the thickness of stock to be removed from the surface of the second roll during rough grinding and finishing grinding operations, respectively, in order to end up with the contour and diameters of the second roll identical to those of the first roll. This involves a total stock removal of ΔR, where $\Delta R = \Delta Rr + \Delta RAf$.

When the code M89 is read and signaled by a momentary voltage on terminal M89 (FIGS. 6A and 15G), the relay RM89 picks up and seals in via contacts RM89*a* and R18*C*. The contacts RM89*b* open to prevent an enabling voltage from reaching the control terminal *s*. The contacts RM89*c* open to prevent any voltage from reaching the terminal *g* when the contacts R20*b* subsequently close. The terminal M89 also connects to the coil of the relay RM80, so that when the M89 code is read, the relay RM80 picks up and the operations described above as an M80 Routine all take place. That is, the numbers *m* and *n* then held in counters 170 and 171 (FIG. 11) are fed to the computer 165, so that their sums, representing the second roll diameter D2, is signaled on the output bus OB. This occurs immediately after the device TD12 and differentiator 267 produces an enabling signal on the terminal *o*1, as previously described. Then, after the time interval created by the device TD13, the relay R20 is energized.

Pickup of relay R20 and closure of its contacts R20*b do* not, however, cause restarting of the tape reader 131. But opening of the contacts R20*a* unseals relay RM80 and removes the input voltages to devices TD11–TD13 so that relay R20 thereupon drops out. During the momentary closure of the contacts R20*c*, a relay R21 is energized through the now-closed contacts RM89*e* and seals in via contacts RM21*a* and RM23*a*.

At the instant the relay R21 is thus energized, a differentiator 271 produces a voltage pulse on the control terminal *t*, so that the computer 165 (FIG. 10) is conditioned to subtract from the number then stored therein and signaled on its output bus (such number being D2) the next number signaled on its input bus.

After an interval measured off by a delay device TD14, a differentiator 272 applies a voltage pulse to the control terminal *u*, thereby opening the gates 169 (FIG. 10) so that the signals (representing the first roll diameter D1) from the D storage device 148 in FIG. 6B are applied to the input bus IB. Almost immediately the difference (D1–D2) is signaled on the output bus OB.

After a further interval created by a delay device TD15, a differentiator 273 applies a voltage pulse to the control terminal *v*, conditioning the computer 165 such that it will divide the number, then contained therein and signaled on its output bus, by two. Almost immediately the result D2–D1/2 is signaled on the output bus OB.

At the end of the period measured off by another device TD16, a differentiator 274 applies a voltage pulse to the control terminal *t*, thereby conditioning the computer so that it will subtract, from the number then stored therein and signaled on its output bus, the next number signaled on its input bus.

Then, after a delay measured off by a delay device TD17, a differentiator 275 will apply a voltage pulse to the control terminal *w*. This voltage pulse opens the readout gates 169*a* (FIG. 10) to apply to the input bus IB signals from the U storage device 147 and representing the number ΔRf. The subtractive result D2–D 1/2 $-\Delta Rf$ is immediately signaled on the output bus OB.

It will be apparent that the quantity D2–D1/2 represents the difference in the radii of the second and first rolls, and if the diameter of the second roll is to be made equal to that of the first, then the total stock removal from the second roll must equal this quantity. However, the amount of stock to be removed from the second roll during finish grinding is determined by the programmer and this number ΔRf is stored in the U storage device 147 when the block N32' is read. By the arithmetic operations described above, the desired stock removal during finish grinding is subtracted from the computed total stock removal which is required in order to determine the amount of stock removal ΔRr which must take place during the rough grinding operations. That is:

$$\Delta Rr = \Delta R - \Delta Rf = (D2 - D1/2) - \Delta Rf \quad (21)$$

By the operations which have been described immediately above, the required stock removal during the rough grinding operations to be performed is signaled as a number ΔRr on the output bus OB of the computer. Of course, if separate rough and finish grinding operations are not necessary, the signaled total stock removal ΔR may be used to command stock removal during one continuous passing operation.

After a time delay created by another delay device TD18, a relay R22 (FIG. 15G) will be energized. Its contacts R22*a* (FIG. 15F) thus close to pick up and seal in the relay RG00. Shortly thereafter, a time delay device TD19 (FIG. 15G) energizes a relay R23 whose contacts R23*a* open to unseal the relay R21. When this happens the relays R22 and R23 drop out. However, the relay RG00 has been picked up and sealed in, and a G00 Routine (as described above in connection with block N25) is initiated and executed with slight modifications because the relay RM89 is now actuated. More specifically, when relay RG00 is picked up, it seals in via contacts RG00*a* and R18*a*. No voltage pulse appears on the terminal *y* because contacts RM89*f* are now open. But because contacts RM89*g* are now closed, a voltage pulse is produced by a differentiator 280 on a control terminal *z* at the instant relay RG00 is energized. This voltage pulse on terminal *z* in FIG. 11 opens the gates 176 so that the number ΔRr then signaled on the output bus OB is preset into the bi-directional counter 170 associated with the rear probe assembly.

Pickup of the relay RG00 closes contacts RG00*b* (FIG. 15B) to cause the motor MRG to drive the rear probe body toward the roll surface. The relay R19 then picks up to close contacts R19*a*. Pulses from the generator Pr (FIG. 11) are counted downwardly in the counter 170, and when the number signaled by the latter is reduced to zero, the decoder produces an output signal EQ. The signal EQ energizes relay R18 in FIG. 15F, and also places a voltage on the associated terminal *g* to restart the tape reader 131. As the tape reader

restarts and relay **18** picks up, contacts **R18***a* open to deenergize relays RG**00** and R**19**; and contacts **R18***c* (FIG. **15**G) open to deenergize the relay RM**89**. The rear probe body has thus been moved inwardly toward the roll through a distance ΔRr from its previous position in which engagement of the probe **81** with the left end of the roll surface would have produced a zero or null signal.

The execution of the M**89** routine, therefore, results in the probe body being preset inwardly by the distance ΔRr signaled on the computer output bus OB rather than by a distance signaled on the output conductors of the storage device **147**.

When the tape reader **131** is restarted at the end of the M**89** Routine, it reads the next block:

N33′
M85
EOB

The execution of this block of data results in an M**85** Routine, previously described to energize the solenoids Rs, Fs and retract the probes **81**, **112**. The tape reader **131** is then restarted.

The next block of data contains commands to move the carriage **42** thirty inches to the left and thereby to return the wheel **21** to the left end of the roll. This next block is:

N34′
Z–030.000
G51
EOB

The execution of a G**51** Routine results, in the manner already described, and the carriage **42** moves to the left so the wheel **21** and probe **81** (rather than the front probe **112**) are now opposite the left end of the roll surface.

The next two blocks N**35**′ and N**36**′ on the sequence tape **131** may be identical to the blocks N**25** and N**26** set forth above with reference to the grinding of the first roll. Accordingly, rough grinding operations are now preformed on the second roll in a manner identical to those described above for the first roll in connection with blocks N**25** and N**26**. However, because the computed number ΔRr has been preset into the counter **170** and used to advance the probe body **88** through a corresponding distance, rough grinding passes on the second roll will continue until stock having a thickness ΔRr has been ground from the roll surface. Then, when the rear probe assembly signals a null at the end of a rough grinding pass, the rough grinding operations will terminate and the tape reader **131** will restart.

At this time, the U storage device **147** in FIG. 6B holds and signals a number ΔRf representing the thickness of stock (here assumed to be 0.001 inch) which is to be removed from the surface of the second roll by finish grinding. The next blocks N**37**′, N**38**′ and N**39**′ on the second roll sequence tape are the same as blocks N**28**, N**29** and N**30** (described above) on the sequence tape for the first roll. Thus, finish grinding operations are now performed on the second roll in a manner identical to that described under the heading "Finish Grinding" for the first roll. It will be understood that the rear probe body is moved inwardly an additional distance ΔRf i.e., a distance of 0.001 inch stored in the U register **147**); the wheel is then infed by an initial increment of 0.0001 inch; and automatic passing for finish grinding is commenced and continued until the rear probe assembly signals a null to indicate that the removal of stock ΔRf in thickness has been accomplished.

In review, it will now be understood that the matching of two rolls to agree in diameter and contour involves the measurement of the first roll diameter D**1** at a predetermined axial location by a sensing assembly comprising the front and rear probes and their associated counters **170**, **171**. The spacings d**1** and d**2** of the first roll surface from reference lines parallel to the Z axis are sensed, and the first roll diameter is signaled by processing of signals to perform the calculation:

$$D1=K-(d1+d2)=m=n$$

previously explained with reference to FIG. **3**. Then, when the second roll is placed in the grinding machine, and before the rough grinding is initiated, the diameter of the second roll at the same predetermined axial location is determined and signaled in the same fashion by the same sensing assembly, viz:

$$D2=K-(d'1+d'2)=m'+n'$$

By processing of signals representing the first and second roll diameters $D1$ and $D2$, the thickness of stock to be removed from the second roll is determined and signaled:

$$\Delta R=D2-D1/2$$

and by substraction of the commanded and signaled finish grinding stock removal ΔRf, the rough grinding stock removal ΔRr is computed and signaled:

$$\Delta Rr=\Delta R-\Delta Rf\ D2-D1/2-\Delta Rf$$

Whether all stock to be removed, ΔR, is taken off in one continuous passing operation, or whether the two components ΔRr and ΔRf are taken off by separate roughing and finishing operations is a matter of choice. But in any event, the sensing assembly (particularly, the rear probe assembly) is then brought into contact with the roll surface at a preselected lengthwise location (which need not necessarily be the same as the predetermined location mentioned above) so as to produce a first signal representing the spacing between a reference line parallel to the Z axis and the roll surface. Preferably this reference line is chosen, by adjustably positioning the rear probe body such that the first signal, represented by the voltage E, is zero. Then, continuous passing and grinding is initiated, with incremental infeed at the end of each pass, and after each pass, the sensing assembly is caused to produce a second signal which represents the then existing spacing between the roll surface on the reference line. When this difference between the first and second signals equals the previously signaled ΔR (or ΔRr, as the case may be), the passing is terminated. Preferably, the difference between the first and second signals equalling the quantity ΔR (or ΔRr) is found by presetting the rear gage body inwardly by the distance ΔR (or ΔRr) and then determining when the voltage E after any given pass has been restored to zero. In those cases where the thickness ΔRr is removed by rough grinding passes, the remainder ΔRf is thereafter removed by finish grinding passes, so that the end result of removing the thickness ΔR is obtained. Thus, the second roll ends up with a profile and diameter corresponding to the first roll.

The remainder of the command blocks on the second roll sequence tape, and the remainder of the operations performed on the second roll, are the same as those described previously in connection with blocks N**31** through N**48** on the first roll sequence tape. Thus, the final diameter of the second roll is sensed and printed out; sparkout passes are executed; polishing passes are executed; and the system is stopped to permit removal of the reground and finished second roll. The latter will have the same contour as the first roll, and its diameters will be the same as those at corresponding axial locations on the first roll, because the diameter of the second roll at one predetermined axial location has been made identical to that of the first roll at the same predetermined axial location.

F. An Alternative Embodiment

It should be understood that the exemplary embodiment of the apparatus described above does not necessarily represent the specific form in which the invention would be manufactured as a commercial product. In the interest of brevity and clarity, the control circuits of FIGS. **15**A–G have been shown as employing relays, but it will be apparent to those skilled in the art that interconnected logic devices such as flip-flops, AND gates, and OR circuits may be used in lieu of relays to perform the various logical operations described. Alternatively, a repetitively cycled time shared computer may be used for the same purpose. Moreover, while the voltage sources between the lines L**1**, L**3** and L**2** have been shown as supplying operating voltages to all of the circuitry, various separate source voltages may be provided for different individual portions of the circuitry. Motor controllers such as full wave SCR controlled rectifier circuits may be provided for each of the drive motors in lieu of the amplifiers shown diagrammatically

in FIGS. 6A, 6B and 15A–G. Finally, it will be understood that wherever isolating diodes and additional time delay devices are required to prevent sneak circuits or improper timing in the circuits of FIGS. 15A–N, these have for the sake of simplicity been omitted from the present drawings and may be added as a matter of ordinary engineering practice by those skilled in the art.

One particularly desirable alternative embodiment of the apparatus is illustrated diagrammatically by FIG. **16** when joined to FIG. 6A in lieu of FIG. 6B, like reference characters being employed to designate components previously described. In this embodiment of FIGS. **16** and 6A, a single, conventional tape reader **300** has its output conductors connected to supply signals into a memory **301** containing a decoder and addressed banks of magnetic cores, flip-flops, magnetic discs or other well known digital memory elements. In the method practiced with this form of apparatus, a first punched tape or record device containing the instruction data for the profile program is first placed in the tape reader, and all of the blocks thereof are read into and stored by the memory **301**. The latter thus becomes the means in which the first program of profile instructions for the director are stored, instead of those instructions being stored on an active profile tape **121** as previously described with reference to FIG. 6B.

After the contouring data have been transferred into the memory **301**, a second punched tape or its equivalent is placed in the tape reader **300**, and the latter is started and stopped as required to read successive blocks of sequence commands into the memory **301**. This second tape and the reader **300** now serve the same functions described above for the tape **131** and the reader **130** in FIG. 6B.

The memory **301** is connected to supply contouring command data signals to the director **125** in much the same way as the tape reader **122** of FIG. 6B supplies such signals, the timing of the transfer being controlled by computer interface circuits **302** which are similar in organization and function to the circuitry previously described with reference to FIGS. **10**, **11**, **12**, **13** and 15A–G. The memory is also controlled by signals from computer interface to apply the necessary mode-determining signals to the director, i.e., the signals heretofore mentioned as being applied to the terminals *c*, *d*, *e* in FIG. 6B. The director returns status or completion signals to the memory and through the latter to the interface circuits **302**.

The interface circuits **302** are connected to supply input signals to, and to receive output signals from a time-shared computer **304** which is programmed to repeatedly execute a series of routine calculations or comparisons, with appropriate interrupts and flags, under the control of a timing cycle generator **305**. The computer may, for example, repeat its whole schedule of operations once every millisecond, with some operations being skipped until called for by control signals from the interface **302**, on data transferred from the memory into the computer.

With such a time shared computer and memory, the system illustrated by FIGS. 6A and **16** will operate to carry out the methods and sequential operations described above with reference to the first embodiment. When any given sequence tape block contains S, W or C codes, these are stored in the memory **301** and signaled by the latter to the D/A converters **153**, **154**, **155** to produce analog voltages which determine the speeds of the motors MH, MW, MC which will obtain when codes M04, M17 and M72 are received and stored so that the computer interface circuits **302** start these motors. Other sequence command codes Z, X, F when stored in the memory **301** are routed to the director **125** and the computer **304** to make the system execute G51, G55, G01 routines as described above in response to reading of these codes from the sequence tape into the memory to condition the interface circuits. When these sequence commands which involve movement of the tool or wheel **21** along the programmed profile are received, then the appropriate ones of the profile data blocks previously stored in the memory **301** are called out of the latter and supplied to the computer and director so that the successive increments of contouring motion by the wheel are executed.

P and U commands from the sequence tape and the reader **300**, or D commands from a typewriter **306**, are transferred into the memory **301** and are used by the interface circuits and the computer to produce the dwell time periods or the presetting of the position of the rear probe body as previously described for the first embodiment. All other coded command words (i.e., M and G codes) are received in the memory **301** to condition the interface circuits **302** so that the various "routines" described above are executed. The interface circuits thus control the steadyrest motor MS during automatic alignment of a roll axis, control the rear probe motor MRG and solenoid RS when the rear probe assembly is to be changed in its status, and control the front probe motor MFG and solenoid FS when the front probe is to be changed in its status.

With the foregoing, additional description is not necessary for those skilled in the art to fully understand the organization and operation of the second embodiment shown by FIGS. 6A and **16**. It is sufficient simply to note that the single tape reader **300** serves first to read the data of a profile contouring program into storage within the memory **301**, and that the system then functions, in response to successive sequence commands read and signaled by the reader **300** into the memory **301** and thence to the interface circuits **302**, to carry out the various operations previously described with reference to the first embodiment. Any sequence command calling for following of the profile results in the appropriate profile data blocks being called out of the memory and utilized by the director **125** and the computer **304** to produce the desired extent to motion along the profile. Other types of sequence commands go into the memory **301** and the latter then controls the interface circuits and the computer to effect execution of the auxiliary routine which is called for. Thus, the system of FIGS. 6A and **16** does not require two tape readers and may respond more quickly to commands for the use of profile data, since the latter are originally stored in and are quickly accessible from the memory **301**.

The invention here disclosed brings to the art new and improved methods and apparatus for quickly and precisely machining or re-machining generally cylindrical workpieces of the type exemplified by the contoured rolls employed in metal rolling mills. Without special attention by a skilled machinist, the contour is located with its point of symmetry at the lengthwise center of the workpiece; the longitudinal axis of the workpiece is aligned parallel with the Z axis of the machine tool; the initial work cutting pass is taken to cut from the larger diameter end toward the smaller diameter end of the workpiece; a predetermined amount of material is removed from the workpiece surface in preselected increments with operating parameters chosen for rough machining; a predetermined amount of material is removed from the workpiece surface in preselected increments with operating parameters chosen for finish machining; the diameter of the workpiece at one or more preselected axial locations is sensed and printed out; sparkout and polishing passes are executed; and any workpiece may be made to end up with a contour and diameters identical to those of a previously machined workpiece.

I claim:

1. The method of controlling a machine tool to shape a workpiece according to a numerically defined path, while performing sequentially a plurality of different operations ancillary to the shaping, comprising the steps of storing in digital form a series of instructions defining successive increments of relative multi-axis movement between a tool and a workpiece which make up a desired profile path, storing in digital form sequential commands designating different ones of a plurality of ancillary routines, a first type of said routines being independent of the profile path and a second type of said routines requiring motions following in whole or in part the profile path, reading the commands in sequence from storage and

causing them to produce in sequential order the ancillary routines designated thereby, and in response to the reading of a command of said second type reading said instructions from storage and causing each to produce in succession the multi-axis incremental movement which it defines until the total movement designated by the commanded second type of routine has been executed, said stored instructions being repeatedly used as often as called for by said commands.

2. The method set forth in claim 1 wherein any command may include an indication of desired feed rate, and multi-axis movement according to the instructions carried out at the feed rate most recently read from storage as a part of a command.

3. The method set forth in claim 1 including the step of signaling the completion of each command after it has been read from storage, and in response to such signaling reading the next command from storage.

4. The method set forth in claim 1 wherein at least some of said commands include a designation of the thickness of material to be removed from the workpiece in the direction of one axis, at least some of the second type of commands call for repeated execution of the contoured path motion with relative incremental infeed of the tool toward the workpiece along said one axis after each such execution, and in the carrying out of the latter category of command characterized by the steps of determining the thickness of material removed after each execution of the path motion, and terminating the repeated execution of the path motions when the measured removal equals the designated removal.

5. The method of controlling a machine tool to shape a workpiece according to a numerically defined path while performing sequentially a plurality of special operations ancillary to the shaping; comprising the steps of storing in digital form a series of instructions defining successive increments of relative multi-axis movement between a tool and a workpiece which make up a desired contoured path; storing in digital form sequential commands designating the sequential steps to be carried out in the shaping of the workpiece; a first type of said commands defining auxiliary functions and a second type of said commands designating relative motion between the tool and the workpiece; reading said commands in sequence from storage and executing each command before reading the next; and in response to the reading of each command of the second type, reading sequentially said instructions from storage and executing each instructed multi-axis increment of movement before reading the next instruction, and terminating the reading of instructions from storage when the total movement equals the motion designated by the previously read command.

6. The method of controlling a machine tool to shape a workpiece according to a numerically defined path while performing sequentially a plurality of ancillary operations, comprising the steps of preparing a first elongated digital record having successive blocks of numerical instructions defining the successive increments of multi-axis relative movement between a tool and a workpiece which make up a desired profile, preparing a second elongated digital record having successive blocks of numerical or code commands designating the successive ancillary operations which are to be performed in sequence, a first type of said commands designating auxiliary functions to be executed and a second type of said commands designating the extent of relative motion to be effected between the tool and the workpiece, passing the blocks of said second record one at a time in sequence through a second record reader to produce a set of command signals corresponding to each block, utilizing each set of command signals corresponding to a command of the first type to carry out the auxiliary function designated thereby; and utilizing each set of command signals corresponding to a command of the second type to initiate the passing of the blocks of said first record one at a time through a first record reader to produce a set of instruction signals corresponding to each block, utilizing each set of instruction signals to cause the tool and workpiece to execute the multi-axis increment motions defined thereby, and terminating the operation of said first reader when the total executed relative motion equals the extent designated by the command of the second type.

7. The method set forth in claim 6 characterized in that said second reader is stopped after the reading of each block of the second record, a completion signal is generated after execution of the command designated by a set of command signals, the second reader is restarted in response to a completion signal; the first reader is stopped after the reading of each block of the first record, a complete signal is generated after execution of the multi-axis increment motion defined by a set of instruction signals; the first reader is restarted in response to a complete signal; and in response to a complete signal when the total executed relative motion equals the extent designated by a command of the second type, the first reader is not restarted but a completion signal is generated to restart the second reader.

8. The method set forth in claim 6 further characterized in that said first record is an endless tape which is repetitively read by successive passings through the first reader, whereby total multi-axis movement in whole or in part following the desired profile may be produced.

9. The method set forth in claim 8 and further characterized in that the desired profile is symmetrical about a reference point on one axis.

10. In a system for controlling a machine tool to cause a tool movable along multiple axes relative to a workpiece to shape the latter with a contoured path while performing sequentially different operations ancillary to the shaping, the combination comprising first means for storing in digital form a series of instructions defining successive increments of relative multi-axis motion which make up the contoured path, second means for storing in digital form sequential commands designating different ones of a plurality of ancillary routines, a first type of said routines being independent of the contoured path and a second type of said routines requiring relative motions between the tool and workpiece following the contoured path in whole or in part, means for reading said command in sequence from said second storing means and in response to each producing the ancillary routine designated thereby, means responsive to reading of a command of the second type from said second storing means for initiating the reading of successive instructions from said first storing means, means responsive to the instructions read for moving the tool relative to the workpiece along the successive increments of said contoured path until the total movement designated by the command of the second type has been executed, and means responsive to the termination of the reading of instructions from said first storing means for initiating the reading of the next command from said second storing means.

11. In a system for controlling a machine tool to cause a tool movable along multiple axes relative to a workpiece to shape the latter with a contoured profile while performing different operations ancillary to the shaping, the combination comprising a first record reader adapted to receive a first elongated digital record having successive blocks of numerical instructions defining the successive increments of multi-axis relative movement between the tool and the workpiece to make up the contoured profile, a second record reader adapted to receive a second elongated digital record having successive blocks of numerical or code commands designating the successive ancillary operations which are to be performed in sequence, a first type of said commands designating auxiliary functions to be executed and a second type of said commands designating the extent of relative motion to be effected between the tool and the workpiece, means for operating said second reader to read one block from said second record at a time, means for executing the command read from a block and restarting the second reader to the next block of the second record, means responsive to the reading of a command of the second type for starting said first reader to read the instructions from successive blocks on the first record, means responsive to the reading of each instruction for causing the incremental relative

multi-axis movement represented thereby and then restarting the first reader to read the next block of the first record, and means for terminating the restarting of the first record when the total executed relative motion equals that designated by the previously read command of the second type and restarting said second reader.

* * * * *