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 a roll of different and undefined 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. 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 preprogrammed values of feed rate, wheel speed, roll speed, continuous infed and incremental infed until a preprogrammed 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 preestablished routines in response to the reading from storage of preprogrammed 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.

9 Claims, 27 Drawing Figures
METHOD AND APPARATUS FOR FINDING THE LENGTHWISE CENTER OF A WORKPIECE

CROSS-REFERENCE TO A RELATED APPLICATION

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

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BACKGROUND OF THE INVENTION

The present invention relates in general to machines and apparatus for the turning 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 8 hour shift. When each worn roll is removed from the mill, there is a need to have its surface refinished or reground 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 reground 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. In the present instance, control of the grinding machine is automated and the speed and precision with which rolls may be ground are facilitated 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. More particularly, the profile of the roll is determined by 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 rolls which are to have the same finished profile. Preferably but not necessarily used in conjunction with such a profile program is a program of sequential commands, prepared individually for each roll or a group of identical rolls 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 roll.

The profile program is prepared by using the lengthwise center of the roll as an assumed zero or reference point and, in most instances, the profile is symmetrical about the lengthwise center. In order to grind the roll to the desired profile as designated by the profile program, it is necessary to determine the actual physical location of the lengthwise center of the roll relative to the grinding machine and to coordinate such location with the profile program prior to actual grinding so that the program will be matched with respect to the roll as positioned axially in the machine.

SUMMARY OF THE INVENTION

The principal object of the present invention is to provide a method and apparatus for finding the lengthwise center of a workpiece such as a roll, and to establish a zero reference for a numerical control contouring program at such center, quickly and preferably automatically after the workpiece has been placed in a machine tool. A related object is to provide a method and apparatus for finding the lengthwise center of the workpiece even though the exact length of the workpiece is not known or measured and even though the axial displacement of the workpiece in a numerically controlled machine tool is not determined by a painstaking and time-consuming set up procedure.

In a more detailed sense, the invention resides in the finding of the lengthwise center of the workpiece by detecting and signaling the physical positions of the end edges of the workpiece in a novel manner as an incident to movement of the machine tool carriage along the length of the workpiece. And the signals thus produced are utilized subsequently to center the carriage relative to the workpiece preparatory to other machine operations, including those operations controlled by the contouring program.

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. 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 spatial 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 latches 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 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 27) is driven to the "hook" or stub shaft at the right end of the roll. The left "neck" of the roll is supported in a left steadyst 29 adjacent a headstock 30 and is drivenly 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 facing 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 and 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 transversely to the longitudinal dimension of the roll. This motion of the wheel is here labeled and designated as negative and positive motion 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 of the desired.

The platform 35 is superimposed on a cross slide 40 mechanism, 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 slideable 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 NZ. As the motor drives the lead screw 46 in one direction or the other, the carriage 42 moves to the right or to 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 slideable relative to back-up pins or wheels 56 fixed to the main carriage 42. As the 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 swivelling 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 controls controlled X axis motion.

The wheel platform 35 is supported on the cross slide 40 with freedom to rock 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 diametrically 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 time relation to movements 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 leading or following 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, Pb and Px are coupled to be driven from or in time relation to the movements of the wheel 21 along the Z, B and X axis. 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 Pb 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 Px 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. When 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 location 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, 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 moveable with the vedge 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-fourth 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 in a circular arc towards 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 a component 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 outer 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 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 line 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 MGR which drives a lead screw 90. A nut 91 fixed to the body 88 is engaged with the lead screw. A feedback pulse generator PR 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 acts 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 of course well known and, as shown in FIG. 12, comprise a primary winding 98 excited from a suitable AC voltage source 100 and inductively 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 V0 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 V0 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 V0 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 V0 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 an 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. 8) 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 inches, 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 PR, and a limit switch LSGF is actuated when the body is fully retracted. The probe body contains a spring 111 and a 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 199 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 $E_f$ is substantially zero. The output of the zero detector $119$ is connected to the coil of a relay $R_{Zf}$, and the latter relay will thus be energized only when the voltage $E_f$ is substantially zero and thus when the probe $112$ is at a centered or null position relative to its body $110$.

5. Proximity Switches

In practice of the invention, one or more workpiece sensors are mounted for movement with the main carriage $42$ to assist in finding a reference point on the workpiece. 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 at 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-fourth 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 between the left or right edge of the roll, that particular switch will be deactivated.

C. The Control System in General

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 $X$ axes in moving from one point to another along the contour path.

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 categories. 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 the commanded subroutines 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 $Z$, $B$ 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 EOF code.

When the reader $122$ is started by a “start” signal, the succeeding 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 EOF 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 $Bf$, $Xf$, $Zf$ 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 $M_z$, $M_b$ and $M_x$. 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 or commanded successively 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 contoured 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, therefore, to compile a library of programs stored on digital media, such as a plurality of the punched tape $121$, defining a relatively small plurality of profiles which will be needed for 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 +ΔZ and −ΔZ from the roll center LC, the total inward motion −ΔX of the wheel will be the same, and obviously the extent of swiveling +ΔB and −ΔB 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 instructions blocks N001 to N100 which define the profile over a distance greater than one-half the length of the roll, i.e., greater than ¼L. The sense of the Z, X and B axis movements are positive, negative and positive, respectively. The blocks N001 to N100 are sufficient to move the wheel 21 to the right, i.e., positively, along the Z axis by a total distance of ¼ L 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 N001 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 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 noted 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 reverse-

ly 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 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 EOB. 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 EOB 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 output of line circuits 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 infed, 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 in 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 converter 155, respectively, which serve to convert the signaled numerical values into proportional analog signals, here assumed to be DC voltages Vz, Vw and Vc. By way of example, if the stored S command is $S_24$, thereby calling for a roll speed of 24 r.p.m., the DC voltage $V_z$ is proportional to the number 24 and is supplied through a suitable amplifier or motor controller 156 (and relay contacts
RM046 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 V\textsubscript{w} is supplied as an input to a suitable controller or amplifier 158 and thence through contacts RM176 (when closed) to the wheel motor MW so that the wheel 21 is driven by that motor at a speed corresponding to the number represented by the command number held in the storage device 144. The output signal from the tachometer 58 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 160a 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 160a 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 V\textsubscript{c} from the digital-to-analog converter 155 is supplied to a summing device here shown diagrammatically as an amplifier 161. A second input voltage to this amplifier is supplied (when the contacts RM74c are closed) from the wiper 162a 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 E\textsubscript{c} from the amplifier 161 is thus proportional to the algebraic difference between the voltage V\textsubscript{c} and the torque load imposed on the wheel 21 by virtue of its engagement with the roll 22. This output voltage E\textsubscript{c} is utilized to control the continuous feed 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 clearer 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 multiple-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 successively signed 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 \textit{r} or \textit{t}, respectively. On the other hand, if a function signal is applied to the control terminal \textit{v}, the computer will divide by two 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 \textit{a} at an open readout gate 168 having its inputs connected to the output conductors of that conductor. Also, by application of control signals \textit{u} or \textit{w}, readout gates 169 or 169a may be respectively opened to place the number held in the D storage device 148 or the U storage device 147 (FIG. 171) 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 \textit{a} or \textit{c}, 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 \textit{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 \textit{a} 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 \textit{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 \textit{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 a zero voltage 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 be 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 pulser 184 and 185 which are respectively coupled to the pulse generators \textit{Pr} and \textit{Pf} 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, 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 \textit{Pf} functions in the same manner.

As noted above, the rear probe counter 170 may be preset by the application of an enabling signal at \textit{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 \textit{z} 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 \textit{p} to a set of presetting gates 188 opens the latter to transfer signals representing a predetermined distance, here 33 inches, from a digital signaling source 189, so as to preset the number 33,000 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., 33,000 inches by application of an enabling signal to a control terminal \textit{q} of presetting gates 190 which have their inputs connected to a signaling source 199a.

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 more 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.

## Setup Procedure

With the rear probe-supporting arm 82 swung upward about its pivot 85 (Fig. 2), a new roll to be finished, or an old and worn roll to be regrind, is placed in the grinding machine 20 with its right and left necks respectively supported by the right and left steadystays 28 and 29 (Figs. 1 and 6A). The clamp or collar 31 is fixed to the right neck so that the headstock is driftingly 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. The 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 0 volts potential, and positive and negative voltage supply lines L1 and L3 through normally open contacts R1c and R1b of a relay R1. The operator need only momentarily close a start switch 5T to energize the relay R1 which then sends in through its normally open contacts R1a, normally closed contacts R0M02, and a normally closed stop switch SP. With this, the contacts R1c and R1b 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 PT1a. 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 PT2a. 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 this 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 point of support in the left steadystay. 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 period 209e 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 S32.
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. In accordance with an important aspect of the invention, the roll 22 need not be carefully placed with an edge lengthwise on the steadyrest 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 gripping the roll with the desired, programmed profile.

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

N01 M61 E08

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, E08, and then stop.

The momentary appearance of a voltage on the M61 terminal of the decoder circuit 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 RT7a. As a result, contacts RM61b and RM61c 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 switch LS1b or LS2b (FIG. 6A) will be actuated. Thus, the normally closed switch contacts LS1b or LS2b 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 PT3a or PT4a 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 LS1b and LS2b will both be actuated, and the contacts LS1b and LS2b 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 set to its centered position under the control of the limit switches LS1 and LS2.

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 PT7a and PT8a 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 LSX1a will be closed to excite the potentiometer PT7 if the platform 35 is on the negative side of its center position. The switch LSX1 is deenergized. Alternatively, the switch LSX2 will be deenergized and its contacts LSX2a 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 LSX1a and LSX2a 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) thereof 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 RZa. The latter are controlled by a relay RZ2 (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 RM86b, so that relay RM84 (FIG. 15C) is energized and sealed in via contacts RM84a, RM85b and its normally closed contacts RM84b 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 RM86c (FIG. 15B) so that a positive voltage is applied to a stepping pulse driver 211 which in turn pulses the motor MB 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 RZ2, thereby opening the contacts RZb (FIG. 15) to drop out the relay RM84. 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 null. The relay RM84
remains sealed in. The relay R8 in FIG. 15D has not been energized, because contacts RM61g 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 RZa (FIG. 15C) to complete a circuit through already-closed contacts RM61d to energize a relay RM85, the latter sealing in through its contacts RM85a and the already-closed contacts RM84c. Pickup of the relay RM85 opens the normally closed contacts RM85b to interrupt the holding circuit for relay RM84, so that contacts RM84b 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 RZa when the contacts RM61d are closed (or for any other reason) the relay RM84 drops out to close contacts RM84b, 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 RZa reopen. Also, when relay RM84 drops out, its contacts RM84c open to break the holding circuit for relay RM85. The normally closed contacts RM84d and RM84c (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 PSRe and PSLc (FIG. 15A) are both closed, while the contacts PSRb and PSLb are open. Similarly the contacts PSLa and PSLc are closed, but the contacts PSLb are open. Under these conditions, the potentiometer PT2 is connected between the lines 61+ and L2 via normally closed contacts RM84d, actuated contacts RM84c and normally closed contacts R2a. This applies a positive voltage across the potentiometer P2t, 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 deactivated because it ceases to sense the adjacent metal of the roll surface.

When the switch PSR deactivates, it contacts PSRe open and its contacts PSRb close. As a result, the "traverse right" potentiometer PT2 is disconnected from the line 61+, but closure of contacts PSRb connects a potentiometer PT2 between the lines 61+ and L2. Accordingly, the wiper P2ta of the latter potentiometer receives a relatively small negative potential, relative to ground or the line L2, and applies such potential to a negative input of the amplifier 126. The motor MZ is energized to move 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 P2t is excited, a relay R2 is simultaneously energized by conduction through a diode 212, and this relay seals in through its own contacts R2c to the negative supply line 61+. Thus, the normally closed contacts R2a are opened, and cannot serve to excite the potentiometer PT2 when the contacts PSRa reclose. Also, the normally open contacts R2b close so as to prepare a circuit for excitation of the potentiometer PT1, but the contacts PSRc are at this time deactivated and open.

After the carriage has 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. 14A. Thus, the proximity switch switch PSR has moved beyond the right edge of the roll and is deactivated, whereas 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. 14B) and is again actuated.

When the left proximity switch PSR is reactivated, its contacts PSRa close, but the potentiometer PT2 is not energized because the contacts R2a are now actuated and open. Its contacts PSRb 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 PSRe close to close a circuit through contacts RM84e, actuated contacts PSRa, actuated contacts PSLa, actuated contacts R2b, and normally closed relay contacts R4d, thus connecting the potentiometer PT1 between the line 61+ and the line L2. As a result, the wiper P1a 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 normally open normally closed contacts R3c to the line 61+. When the relay R3 picks up, its contacts R3c in FIG. 10 close thereby connecting the output terminal 180 of the potentiometer 178 to the "up" input of the bidirectional counter 166 through normally closed relay contacts R4a. It will be noted that at this time the contacts RM61r, RM61f and R4a 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 is initially moved to the right until the proximity switch PSR ceased to sense the adjacent roll surface (FIG. 14A) and was then moved slowly back to the left until the proximity switch PSR again sensed the roll surface (FIG. 14B), 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. 14C) and becomes deactivated. 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. 14B to its position shown in FIG. 14C.

When the left proximity switch PSL reaches the position illustrated by FIG. 14C, it will be deactivated. As a result, the contacts PSLa will open, deenergizing the potentiometer PT1, so that the motor MC is stopped. However, the contacts PSLb will close to complete a current circuit for the line 61+ through a potentiometer PT6 to the line L2. Accordingly, a positive voltage will appear on the wiper P6a 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 PS\textsubscript{Lb} will result in energization of a relay R\textsubscript{4} by conduction through a diode 215, the relay sealing in through its normally open contacts R\textsubscript{4d} leading to the line 61+. When the relay R\textsubscript{4} picks up, its normally closed contacts R\textsubscript{4e} in FIG. 10A open to break the previous connection to the up input terminal of the counter 166, and the contacts R\textsubscript{4b} 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 P\textsubscript{T6}, the pulses from the pulse generator P\textsubscript{z} 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. 14D and the left proximity switch PSL is again actuated by 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. 14B to that shown in FIG. 14C was registered positively in the counter 166, and the distance moved by the assembly 80 in moving from the position shown in FIG. 14C to that shown in FIG. 14D 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. 14B and 14D. As noted above, where the rear probe assembly 80 has been moved to the right the position shown by FIG. 14D, the switch PSL is again actuated. Its contacts PSL\textsubscript{c} thus close, but this produces no effect because the contacts R\textsubscript{4d} are now open. Its contacts PS\textsubscript{Lb} open to deenergize the potentiometer P\textsubscript{T6}, so that creeping drive to the right by the motor MZ is terminated. Its contacts PSL\textsubscript{e} (FIG. 15B) close, and because the contacts R\textsubscript{4b} are now closed, a voltage is supplied from the line 61- through normally closed contacts R\textsubscript{6b} 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 control terminal a in FIG. 14. To momentarily open the readout gates 168, and to cause the carriage to then be transferred to the input bus IB and that 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 TD\textsubscript{1} (FIG. 15B) 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 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 TD\textsubscript{2} 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 therefore on 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 dimensions C shown in FIG. 10, and then to count until it is then positively set to hold onehalf of its original number, i.e., to store and signal a number representing one-half of C as shown in FIG. 14E.

The input voltage supplied to the differentiator 219 is also passed through a second time delay device TD\textsubscript{3} to energize a relay R\textsubscript{5} (FIG. 15B). Thus, the relay R\textsubscript{5} 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 R\textsubscript{6b}, PSL\textsubscript{c}, and R\textsubscript{4b} remains complete. When the relay R\textsubscript{5} picks up, its contacts R\textsubscript{5a} in FIG. 15A close so that the potentiometer PT\textsubscript{2} is again connected via the normally closed contacts RM\textsubscript{84d} to the actuated contacts PSL\textsubscript{c} and the contacts R\textsubscript{5a} between the lines 61+ and L2. Thus, a relatively large positive voltage appears on the wiper PT\textsubscript{2a} 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 R\textsubscript{6b} in FIG. 10 are still closed, so that pulses from the generator P\textsubscript{z} 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 R\textsubscript{5a} in FIG. 15B to energize a relay R\textsubscript{6} which seals in via its contacts R\textsubscript{6a} leading to the line 61+.

In consequence, the normally closed contacts R\textsubscript{6b} open, thereby deenergizing the relay R\textsubscript{5}, and causing the contacts R\textsubscript{5a} 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 switch 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 R\textsubscript{6} 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 R\textsubscript{7b}, it is caused to apply a time delay device TD\textsubscript{4} which after a short delay energizes a relay R\textsubscript{7} P\textsubscript{T}. Once the relay R\textsubscript{7} opens its normally closed contacts R\textsubscript{7a} (FIG. 15A) to interrupt the holding circuit from the relay RM\textsubscript{61}. Accordingly, the relay RM\textsubscript{61} is deenergized, and the execution of the center finding and the reference setting routing is completed. The contacts RM\textsubscript{61b} and RM\textsubscript{61c} open to remove the supply voltages from the lines 61+ and 61−, so that the limit switches LSB\textsubscript{1}, LSB\textsubscript{2} can no longer affect the motor MB, the limit switches LSX\textsubscript{1} and LSX\textsubscript{2} can no longer affect the motor MX, the potentiometers PT\textsubscript{1}, PT\textsubscript{2}, PT\textsubscript{5} and PT\textsubscript{6} can no longer affect the motor MZ; and the relays R\textsubscript{2}, R\textsubscript{3}, R\textsubscript{4}, R\textsubscript{5}, R\textsubscript{6} and R\textsubscript{7} are all deenergized. When the relay R\textsubscript{7} is momentarily energized prior to drop-out of relay R\textsubscript{61}, the contacts R\textsubscript{7b} and RM\textsubscript{61c} in FIG. 15D are both closed for an instant, and the relay R\textsubscript{8} picks up momentarily to close its contacts R\textsubscript{8a}, causing delay device TD\textsubscript{5} 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 of a 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 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 steadiest rest 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 machines 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 steadiest is then moved to swing the roll and its longitudinal axis about a point at the other steadiest 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 that is desirable to fulfill a system requirement that each block contain only one G code or only 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)
- MO4 (start MH)
- M17 (start MW)
- P4 (delay duration)
- G04 (time delay)
- E08 (end of block)

The block number code NO2 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 head-stock 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 make the voltage Vs of proper magnitude such that the amplifier or controller 156 will energize the motor MH whenever the contacts RMO46 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 on 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 RM17b 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 MO4 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 RMO46, and the normally closed contacts RM05a. With this, the contacts RMO46 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 RM17a and normally closed contacts RM18a. With this, the contacts RM17b in FIG. 6B close so that the motor MW is energized and begins to rotationally drive the wheel 21.

404 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 the fractions 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 223 in FIG. 15C. The dwell timer has four control terminals P1-P4 and, when started, it will cause the dwell timer to 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 RGO46 close until it
produces an output voltage which serves to energize the relay R9.

When the GO4 code is read and signaled, the output terminal GO4 of the decoder circuits 134 receives a momentary voltage which is applied to the correspondingly labeled terminal GO4 in FIG. 15C. Accordingly, a relay RGO4 picks up and seals in through its own contacts RGO4a and normally closed contacts RGO4b. At the same time, relay contacts RGO4b 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 R9a open to break the holding circuit for the relay RGO4, and the latter thus drops out. This same voltage applied to the relay R9 is also passed through normally closed relay contacts RMO2 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 to 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 b1 and b2 will be located 2 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 b1, 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:

\[
\begin{align*}
&\text{NO3} \\
&\text{F120} \quad \text{feed rate} \\
&\text{Z+073.000} \quad \text{Z displacement} \\
&\text{G51} \\
&\text{EOB}
\end{align*}
\]

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 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 in a direction and through a distance corresponding to the sign and magnitude of the number then stored in the Z register 140. When that 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 RGS1 is energized and seals in through its own normally open contacts RGS1a and normally closed contacts R8c. 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 Y 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 control terminal at the director 125, this voltage is applied to the correspondingly labeled terminal in FIG. 15D and passes through the now closed contacts R51b to energize the relay R8. In consequence, the contacts R8c close so that after a short time delay the time delay device TDS 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 contacts R8c open to break the holding circuit for the relay RGS1, 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:

\[
\begin{align*}
&\text{NO4} \\
&\text{M70} \\
&\text{EOB}
\end{align*}
\]

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.
1SD, causing the relay RM70 to pick up and to seal in through its own contacts RM70b and normally closed contacts CSb. As a result, the circuits RM70c also close. At this time the feeder 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 LS1a in concreteness 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 PT9a. 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 feeder 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 LS1a and LS1b in FIG. 15D will be respectively opened and closed. With this, the potentiometer PT9 is deenergized, and the circuit is established through normally closed contacts CSc to excite a feed potentiometer PT10. Accordingly, a smaller positive voltage appears on the wiper PT10a 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 CSc open to deenergize the potentiometer PT10, thereby stopping the cross slide motor MC; its contacts CSa (FIG. 15D) close to complete a circuit through the now-closed contacts RM70c so that relay R8 is picked up and its contacts R8c close to create a tape reader starting voltage on the control terminal g; and its contacts CSb open to drop out 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.

a. 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 -0.0050, 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 RBd 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 command 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 RG5c and thus momentarily energizes the relay R8. Accordingly, the contacts R8c close and a voltage pulse appears on the control terminal g, thereby restarting the sequence tape reader 131. The contacts RBd 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 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 b1 (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.

c. 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=-0.250 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 b1), 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 grinding of the left gage band b2. This next block of data may include:

N07 F120 Z=-146.0000 G51 E0B

This seventh block of data calls for the execution of G51 Routine wherein the wheel 21 is to be moved at a rate of 120 inches/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. Gridding 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 at which it occupied at the time when the gridding of the right gaging band was completed.

In other words, the center of the wheel face at the completion of the gridding of the left gaging band b2 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 gridding machine. The left gaging band b2 may be slightly greater or less in depth than the gaging band b1 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 gridding 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 b2 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 '31' replaces the 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 34. According to the momentary voltage appearing on the M86 output terminal of the decoder circuits 34, 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 RZb. The RM86b contacts therefore close to energize the relay RM84 (FIG. 15C) which seals in through its own contacts RM84a and the normally closed contacts RM85b. As a result, the normally closed contacts RM84b 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 RM84c in FIG. 15D close, but the relay RB is not energized because the contacts RM86d are now open. Also, when the relay RM86b picked up and sealed in, its contacts RM86c (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 RZb in FIG. 15B to unseal the relay RM86. Also, the contacts RZa in FIG. 15C close, but this produces no effect upon the relay RM85 because the contacts RM61a 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 b2.

When opening of the contacts RZb drops out the relay RM86, the contacts RM86b also open but the relay RM84 remains sealed in through its contacts RM84a and normally closed contacts RM85b. The contacts RM86c close (FIG. 15D) thereby completing the circuit through the contacts RM61a, RG5c, RM86d, RM84c (now actuated) and RM85d to energize the relay RB. The contacts RZa close so that after the delay of TDS 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 to energization of the associated solenoid RS. Thus the next block now being read from the sequence tape includes:
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 RM85a and the now-closed contacts RM84c. When the relay RM85 picks up and seals in, its contacts RM850 open to unseal relay RM84, thereby closing contacts RM84c to energize solenoids RS and FS. Contacts RM84c open to unseal and drop out relay RM85. In Fig. 15D, therefore, the contacts RM85d first open to drop out relay R8, but the opening of contacts R8a produces no positive voltage pulse on terminal g, so reader 131 is not restarted. Just after contacts RM85d open, contacts RM84c open, but during the interval that relay RM85 is energized, contacts RM85e are closed to position the energized pulse to delay device TDSa, which thereafter applies an energizing pulse to delay relay R8. The contacts R8c 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 RM84c 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 89 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 b1 (Fig. 4), the next operation is to return the carriage to the right so that the probe 81 is positioned opposite the right gaging band b1. 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 recalled 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 b1 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 b1. 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 RM84e and the normally closed contacts RM85b. This is the beginning of the execution of an M84 Routine. That is, when the relay RM84 picks up, its contacts RM84b 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 b1, and the LVDT 95 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 b1 and b2, 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 b2 and b1 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 steadystre.

The dimension A represents the longitudinal distance between the point C and the location of the center of the left gaging band b2. 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 inches) at the time the sequence program is prepared. Thus, the dimensions A and G for any given roll are definitely known at the time the program is prepared.

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:

\[ E' = (G−A)/2G \cdot Eo \]  

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 b1. 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 p1 from the reference line 232 to the surface of gaging band b2, and (b) the distance p2 from the reference line 232 to the surface of the gaging band b1. That is,

\[ Eo = k \cdot \Delta \]  

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 its left position, the initial voltage Eo by its negative polarity would indicate the sense or sign of the difference \( \Delta \).

To bring the roll axis into alignment with the Z axis of the machine, the right steadystre and thus the right neck of the roll must be moved forward 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 its initial setup, moving the right steadystre forwardly until the point Q on line 234 coincides with the point T on line 235. In such aligning action the point
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 $E_0$ 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 EOB code), a momentary voltage appears on the M64 output terminal of the decoder circuits 134. This momentary voltage also appears on the same terminal M64 shown in FIG. 15E, so that a relay RM64 is picked up and sealed through its contact 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 RM64b 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 $E_0$ which represents the difference $\Delta$. 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 240a will be held charged with the voltage $E_0$ appearing thereacross. In the example represented by FIG. 8, the initial difference voltage $E_0$ will have the positive polarity labeled in FIG. 12.

After the time delay produced by the device TD6, the relay R111 (FIG. 15E) will pick up and remain energized so long as the relay RM64 is energized. Thus, the contacts R111c in FIG. 12 will open to disconnect the probe signal voltage $E$ from the input of the memory amplifier 240. Also, the contacts R11b and R11c 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 209a 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 $E_0$ applied to the entire potentiometer. Thus, it may be understood that the input voltage $E'$ applied through the contacts R11b 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 R11c to the input terminal on the right side of the summing 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 $E_0$. Therefore, the output voltage of the summing amplifier $E_0$ to the steadyrest motor M5 will energize the latter causing it to drive the headstock forward, i.e., in a positive direction along the axis $X$ and transverse to the axis $Z$ (see FIG. 6A). The steadyrest motor will continue to run until the headstock becomes aligned with the axis $X$ of the cutting 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 $D_1$ the sequence tape reader was restarted immediately. The next block on the sequence tape contains the following data:

Q on axis 234 must move through the distance $d$ and thus the point $F$ (on band $b_1$ and engaged by probe $B_1$) must likewise move through the distance $d$ to the point labeled $J$. When that happens, the displacement of the probe $B_1$ 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 $D_2$ and $D_1$ at the right and left gaging bands is equal to the distance $\Delta$, viz:

$$D_2 - D_1 = \Delta$$  \hspace{2cm} (4)

Also, the distance $\Delta$ is 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:

$$d = \Delta - e$$  \hspace{2cm} (5)

Further, the distance $K$ plus the distance $d$ is equal to the radius $R_2$ at the right gaging band, that is:

$$d = R_2 - K$$  \hspace{2cm} (6)

The two triangles CH1 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:

$$\frac{HUCI}{QT} = \frac{QT}{CT}$$  \hspace{2cm} (7)

But the length $HI$ is equal to $(R_1 - K)$; the length $CT$ 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:

$$(R_1 - K) = d d(A+G)$$  \hspace{2cm} (8)

The quantity $R_1 - K$ can be expressed in different form by substitution from Equations (4a), (5), and (6):

$$R_1 - K = R_2 - \frac{\Delta}{2} - K = d - \frac{\Delta}{2} + e = \frac{\Delta}{2} - e$$  \hspace{2cm} (9)

Substituting $R_1 - K$ from (9) and $d$ from (5) into (8):

$$\frac{\Delta}{2} - e = \frac{\Delta}{2} - e$$  \hspace{2cm} (10)

Simplifying Equation (10) yields:

$$\Delta = A - G = \frac{1}{2} (G - A)$$  \hspace{2cm} (11)

But the original difference $\Delta$ is proportional to the original voltage signal $E_0$, as indicated by Equation (3). And when the probe is deflected from a null position only by a distance $e$, the probe voltage signal $E$ at that time will be proportional, i.e.,

$$E = ke$$  \hspace{2cm} (15)

Thus, Equation (14) can be rewritten:

$$E/k = E_0/k = (G-A)/2G$$  \hspace{2cm} (16)

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 $D_1$ the sequence tape reader was restarted immediately. The next block on the sequence tape contains the following data:

3,660,948

$34 N14 M64 EOB$
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 RZSa in series therewith are now open for a reason which will be explained below, and thus the relay R13 will now 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 voltage of the output axis from 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 contacts 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 R13a 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 RM64b in FIG. 12 open so that even though the contacts R11are close, the probe signal voltage E is not again applied to the input of the memory amplifier 240. Also, the relay contacts R11b and R11c reopen to interrupt the input circuits for the summing amplifier 241.

When the relay R13 is energized by conduction through contacts R12a and R2Sa, 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 probe 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 the 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. In the grinding of the roll surface is always initiated by the 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 M64 routing to adjust the right steadyrest, as described above, the contacts RM64b (FIG. 15E) will be closed. The contacts R14a will be closed only if the diameter of the right gaging band 51 is larger than that of the left gaging band 52 (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 roller 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 M64 alignment routine, the polarity of the probe voltage E is sensed, and a relay R14 is 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 its own contacts R14a and normally closed contacts RM19b, and in that event, the contacts R14b 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  E0B
N16  DE  M85  E0B
N17  DE  Z = 140.000  G51  E0B
N18  M19  E0B
N20  DE  M85  E0B
N21  DE  Z = 003.000  G51  E0B
N22  M70  E0B
```
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 M64 alignment routine is complete (with the probe 81 engaged with the surface of band b1 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 M64 routine is complete, the tape reader begins reading block N15, and first read 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 E0B 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 i of FIG. 15E. This picks up relay RM19 which seals in via its contact RM19c and normally closed contacts RG01d, RM70d; 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, it contacts RM19b open to drop out relay R14; and the contacts R14b 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 N20 (and does not delete it). When the M05 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 M05 Routine), and the reader 131 is restarted.

The next block N22 results in the reading of an M70 code and the execution of an M70 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 M70 is picked up during this operation, the contacts RM70d (FIG. 15E) open to unseal relay RM19. 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 M64 alignment routine, the relays R14 and RBD will both be energized and a voltage to enable block delete operation will not be present on terminal i (FIGS. 15E and 6B). Therefore, when the tape reader begins reading block N15 (see above) it will ignore the DE code therein, read the M06 code, read the E0B code and stop. An M06 Routine, as described above, will now be executed, resulting in the motor MRG driving the probe 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 R8 picks up via current...
When the S20 code is read and signaled, the number "20" replaces the previous number "24" in the storage device 140, so the head 20 is now controlled to drive the roll 22 at 20 r.p.m. When the W50 code is read, the number "40" 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 F005 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 C20 is read, the number "20" is stored in the register 145, so voltage Vc takes on a magnitude which represents a desired rate of continuous infed 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 -0.0005 is stored in the register 141. Then the G01 code is read and signaled, and the E08 code is read to stop the reader 131. The system now executes a G01 Routine (described above) to feed the wheel into the roll a first X axis increment of 0.0005 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 forward 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 infed 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
E08

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 infed 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 direct action. The number represents the extent of motion along the Z axis during each pass as explained below. It will be seen from the example of FIG. 7 that the wheel must travel 152 inches along the Z axis to move from the end position 21(4) to position 21(5) or vice versa.

When the M72 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 RM72 (FIG. 15F) which seals in via contacts RM72a, REPc, and RM73c. Therefore, the contacts RM72b (FIG. 15D) close to supply the voltage Ec from FIG. 6B 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 infed 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 162a. Thus, if the wheel feeds inwardly too fast and the torque load thereon increases, the voltage Ec is reduced and the rate of infed decreased. The code M72 may be considered as commanding the system to "start continuous infed with load control."

g55 Routine

When the G55 code is read and signaled a "continuous passing" operation is initiated. The appearance of a momentary voltage on the terminal G55 (FIGS. 6B and 15E) causes energization of a relay RG55 which seals in through its own contacts RG55a and normally closed contacts R16b. An enabling voltage therefore passes through normally closed contacts REPb and appears on the terminal k (FIGS. 15E and 6B). 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 by the Z storage register 140. If the existing wheel position is positive (right), the motion is negative (left) along the Z axis, and vice versa. 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 G55 command, moved along the profile to the other end of the roll wheel 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 RG55b (FIG. 15E) to energize an "end pass" relay REP, which seals in via contacts REPb, R16c, and R17d. This opens contacts REPb (FIG. 15E) to remove the voltage from terminal k, so the director 125 is taken out of its profile pass mode. Also, contacts REPc open to deenergize relay RM72 (FIG. 15F) so that contacts RM72b (FIG. 15D) open to terminate the continuous infed of the motor MC. Also, contacts REPb (FIG. 15C) close to energize relay RM84 which seals in via contacts RM85b and opens its contacts RM84b 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 to a predetermined amount, in this case to agreement with the surface of the smallest gaging band (upon which the rear probe was previously null). 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 1 — 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 REPd (FIG. 15F) will be closed because relay REP is energized at the end of any grinding pass; the contacts RM84 will close when relay RM84 is energized to release the rear probe 81, as just described, so that a time delay device TD8 will produce an output voltage at an instant shortly after the contacts RM84 close; and the contacts R+ will be actuated and closed (with the contacts R+Ec open). Thus, a relay R15 will be energized by current flow through normally closed contacts R17a.

As a result, the contacts R15a (FIG. 15E) close to energize relay RG81, which seals in via contacts RG01a, R17c, and R86. The system now executes a G01 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 N24 (see above) this stored number is -0.0004. Therefore, the wheel is fed inward by an increment of 0.0004 inch before the next grinding pass begins. This is termed the incremental infed. When such G01 Routine is completed and the director produces a momentary voltage on its terminal h, the relay RG15 (FIG. 15D) is not energized (and the tape reader 131 is not restarted) because the contacts RG55c are open during execution of any G55 Routine. However, the voltage at the same terminal h in FIG. 15F does pass through the now-closed contacts RG55d, and a relay R17 is picked up. In consequence:

a. Contacts R17a open momentarily to drop out relay R15.

b. Contacts R17b (FIG. 15C) close momentarily to pick
up relay RM85, so that RM84 is deenergized and the probe 81 is retracted, as previously explained. The relay R8 is not energized when contacts RM85c are open, because contacts RG55e are now open. Relay RM85 drops out when contacts RM48c are open.

c. Contacts R17c (Fig. 15E) open momentarily to drop out relay RGO1.

d. Contacts R17d open momentarily to drop out relay REP.

e. Contacts R17e (Fig. 15F) close momentarily to energize relay RM72 which seals in via contacts RM72e, REPc and RM73e — so that continuous infed drive by the motor MC is restored by closure of the contacts RM72b in Fig. 15D.

When relay REP is thus deenergized, its contacts REPb (Fig. 15E) 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 infed, 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+e will be open and the contacts R+e (Fig. 15F) will be closed when the device TDS produces an output voltage after closure of the contacts RM84c when the probe 81 is released. Therefore, the relay R16 instead of the relay R15 will be energized. In consequence:

a. Contacts R16b (Fig. 15E) open to seal relay RG55.

b. Contacts R16c open to seal relay REP. The contacts REPb close, but no voltage appears on terminal k because contacts RG55e are open.

c. Contacts R16d (Fig. 15C) close to energize relay RM85 which seals in, so that contacts RM85b open to drop out relay RM84, thereby closing contacts RM84c 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 RM85d (Fig. 15D) open substantially simultaneously with reclosure of the contacts of the relay RG55.

However, the contacts RM85c close, so that after a delay measured off by a device TDSa, the relay R8 picks up momentarily. This closes the contacts R8c and after a delay created by device TDSa, a voltage pulse appears on the terminal g, thereby restarting the tape reader 131 (Fig. 6B).

e. When relay REP drops out, its contacts REPd (Fig. 15) open to deenergize relay R16, but the latter does not restore its contacts to a deactivated 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 infed 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 "sparkled" 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
G80
E08
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 port. The code G80 is then read and signaled, and reading of the E08 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 RG00a and R18a. 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 116 so that the number (here 0.0090) 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 RG00b (Fig. 15B) to apply a positive input voltage to the driver 211 so that motor MRG is energized to stop 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 stops the probe body inwardly, pulses from the feedback generator Pr (Fig. 11) are applied by the pulse 184 to the down input of the counter 170. When the counter counts down to zero from the number (0.0090) 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 R19a (Fig. 15F) to energize a relay R18. The contacts R18a open to deenergize relays RG00 and R19, so contacts RG00b 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 dropout of relay R19 and opening of contacts R19a 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 (0.009inch) 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
The block N26 is similar to block N23 treated above, and the responses to reading of the codes will be the same as those 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 F606 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 infed 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 GO1 Routine to give the wheel an initial incremental infed of 0.0009 inch into the surface of the roll.

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

```
N27
X-0.0009
X+152.000
G55
M72
EOB
```

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 infed. 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 Grind

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 little 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
F630
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 feed 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 infed 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
EOB
```

The response to the reading of these data is similar to that described above for block N24, except that the incremental infed at the end of each grinding pass will be only 0.001 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 infed 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 instrumentality associated with the machine.

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

```
N31
X+0.0100
G01
EOB
```

These data 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 GO1 Routine, as described above, with the wheel thus being moved outwardly 0.01 inch and at a feed rate of 30 inches/min. (F630 having been stored in register 152 from reading of block N29). The next block of sequence command data is then read and contains:

```
N31a
P4
G04
M83
M82
EOB
```

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 Routine) until the other commanded functions have been completed.

The codes M83, M82 and EOB 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 RM83a and the normally closed contacts LSRGa of the limit switch LSRG associated with the rear probe assembly (FIG. 4). Relay RM82a seals in through its contacts RM82a and the normally closed contacts LSFGa of the limit switch LSFG associated with the front probe assembly 106. The contacts RM83b 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 RM82b close to apply a negative voltage to drive 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 LSRGb and LSFGb (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
19, so that the number 33.0000 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, 33.0000).

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 Cm 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 predetermined and known quantity, here labeled and assumed to be 33.0000 inch (hereafter referred to simply as 33 inches). If the roll 22 is placed in the machine with its cross-sectional center Cr coincident with the machine center Cm, 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 Pr were counted down in the counter. The counter would then hold a number representing the roll radius R1, and 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 Cr displaced from the machine center Cm, 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 alone would be inaccurate because of the extent of the displacement of the centers Cm and Cr 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 33.0000. The distances from the center Cm 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 inches. 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 Pr and Pz 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 N31a 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:

```
N34
M86
E0B
```

Accordingly, the relay RM19 (FIG. 15E) is energized and sends a command via its contacts RM19a and normally closed contacts RM70d. At this time, the dwell timer 121 is either the right or left end of the roll surface, the relay RL in FIG. 15E will be deenergized or energized, and the contacts RL4 in FIG. 15E will be open or closed, respectively. Therefore, when relay contacts RM19c 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 TDS, 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 read number 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 N33 and N34 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 RM86d (the contacts RM86e 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 Pr 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 trigger 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 15G), a relay R87 pops up and seals in through its contacts RM87a and the normally closed contacts RZF7b. Thus, contacts RM87d (FIG. 15D) open so that relay R8 will not be energized until the contacts reclose after contacts RM84e subsequently close. The contacts RM87e (FIG. 15C) close to energize the relay RM84 which seals in via RM84a and RM85b. As a result contacts RM84b open to deenergize RS, FS and thus to release the probes. Contacts RM87c close to apply a positive voltage to the pulse driver 214, so that the motor MFG is driven 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 EF (FIG. 13) is reduced to zero, and the zero detector 119 thereupon energizes the relay RZF7. This results in opening of the normally closed contacts RFZ67 in FIG. 15D to drop out the relay R87. Therefore, the contacts RM87c open to stop the motor MFG; and contacts RM87d in FIG. 15D reclose so that the relay R8 is energized through the now-closed contacts RM84e and the normally closed contacts RM85d. The relay contacts R8a 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 Pr were counted downwardly in the counter 171 (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 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 M55 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 pops up and seals in via its contacts RM80a and normally closed contacts R20a. 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 counter 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 counter 165.

The output of the device TD11 forms 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 o1. This voltage appears on the correspondingly labeled terminal labeled terminal o 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 supplies a voltage pulse through normally closed contacts RM85b 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 g 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 R20a 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 R20b 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 Cm 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 Pr and Pf measure off and signal the distances d1 and d2 through which the bodies move to null the probes in contact with the roll surface. The distances m and n are thus expressed:

\[ m = K/2 - d1 \]  
\[ n = K/2 - d2 \]

Since the number K/2 (here, 33,0000) was first preset into the counters 170 and 171 and the numbers d1 and d2 are subtracted therefrom by pulses from the differentiators 265 and 266, 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

\[ D1 = m + n \]

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 d1 and d2, registered negatively in the counters 170, 171 which have both originally been set to hold the number 33,0000, or collectively to hold number 66 inches. Therefore, the diameter D1 is expressible:

\[ D1 = K - (d1+d2) = m+n \]

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 D1 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 "sparkling" and "polishing" operations. These do not involve any incremental infed 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 en-
gage ment 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 RG01d (FIG. 15E) open, thereby deenergizing the previously sealed-in relay RM19. The contacts RM19c open and drop out the relay RBd. 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 now 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 now 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 RM74a and the normally closed contacts RM72a. As a result, the contacts RM74c (FIG. 6B) open to disconnect the potentiometer wiper 162a from the input to the amplifier 161. Also, the contacts RM74b (FIG. 15F) close to energize the relay RM72, so that contacts RM72b (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 data 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, mirror-like 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 RM73b open to break the holding circuit for relay RM72 so that the contacts RM72b in FIG. 15D open, thus stopping the motor MC and terminating the continuous infeed. Also, the contacts RM73a 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 at the speed 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 N46 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
EOB

N47
Z-152.000
G51
EOB
```

The commands of blocks N46 and N47 are executed as G51 Routine, as previously described. The wheel 21 thus moves along the profile in light contact with the roll surface (but with no incremental or continuous infed) 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
EOB
```

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 hereinafter described. The contacts RG04d 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 RM01e. 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 EOB.

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 15C), a relay RM02 will pick up and seal in via its contacts RM02a. The other contacts of this relay produce the following action:

1. Contacts RM02b and RM02c 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 116 and 118 will be driven by their corresponding step motors to fully retracted positions, as described above with reference to block N31.
2. The contacts RM02d 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 RM02e in FIG. 15A will open, but the holding circuit for relay R1 remains complete because the contacts RG04d are now closed.

When dwell timer 225 (FIG. 15C) times out, its output voltage will not reach the terminal g because contacts RM02g are now open. But relay R9 is energized so its contacts R9a open to drop out relay RG04. Thus, the contacts RG04d in FIG. 15A open to break the holding circuit for relay R1. The contacts R19 and R1c 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 RM04b and RM17b (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 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 131a 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 D00, D00, D00 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 N01-N23). Thus, the sequence tape for the second roll will be read through the first twenty-three 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 are all 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', N24a' through N31' will be identical to the blocks N31, N31a through N38 described above with reference to the first sequence tape.
These blocks N34' 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 to their respective bodies 88 and 110. The two probe bodies have been located, however, such that if their probes were released opposite a point 2 inches to the right of the left end of the roll surface, then the probe assembly signals E and Ef 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 0.001  M89  E8B

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 a 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 ∆Rr and ∆Rf 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 ∆R, where

\[ ∆R = ∆Rr + ∆Rf. \]

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 RM89e and R18a. The contacts RM89e open to prevent an enabling voltage from reaching the control terminal s. The contacts RM89c open to prevent any voltage from reaching the terminal g when the contacts R20b 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 t1a, as previously described. Then, after the time interval created by the device TD13, the relay R20 is energized. The pickup of relay R20 and closure of its contacts R20b do not, however, cause restarting of the tape reader 131. But opening of the contacts R20a 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 R20c, a relay R21 is energized through the now-closed contacts RM89c and seals in via contacts RM21a and RM23a.

At the instant the relay R21 is thus energized, a differentiator 271 produces a voltage pulse on the control terminal i, 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 i, 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 169a (Fig. 10) to apply to the input bus signals from the U storage device 147 and representing the number ∆Ar. The subtractive result D2–D1/2 – ∆Ar 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 ∆Ar 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 ∆Ar which must take place during the rough grinding operations. That is:

\[ ∆Ar = ∆R – (D2–D1)/2 – ∆Ar \]  

(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 ∆Ar 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 ∆Ar 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 R22a (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 R23a 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 GOO 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 RG00a and R18a. No voltage pulse appears on the terminal y because contacts RM89y are now open. But because contacts RM89c 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 ∆Rr then signaled on the output bus OB is preset into the bidirectional counter 170 associated with the rear probe assembly.
Pickup of the relay RG00 closes contacts RG00b (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 R19a. 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 termalg to restart the tape reader 131. As the tape reader restarts and relay 18 picks up, contacts R18b open to deenergize relays RG00 and R19, and contacts R18c (FIG. 15G) open to deenergize the relay RM89. The rear probe body has thus been moved inwardly toward the roll through a distance $\Delta Rr$ 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 M89 routine, therefore, results in the probe body being preset inwardly by the distance $\Delta Rr$ 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 M89 Routine, it reads the next block:

N33'  
M85  
EOB

The execution of this block of data results in an M85 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 30 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  
GS1  
EOB

The execution of a GS1 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 N35' and N36' on the sequence tape 131 may be identical to the blocks N25 and N26 set forth above with reference to the grinding of the first roll. Accordingly, rough grinding operations are now performed on the second roll in a manner identical to those described above for the first roll in connection with blocks N25 and N26. However, because the computed number $\Delta R$ 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 $\Delta R$ 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 $\Delta Rf$ 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 N37', N38', and N39' on the second roll sequence tape are the same as blocks N28, N29 and N30 (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 $\Delta Rf$ (i.e., a distance of 0.001 inch stored in the U register 147); the wheel is then infed by an initial increment of 0.001 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 $\Delta Rf$ 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 $D1$ at a predetermined axial location by a sensing assembly comprising the front and rear probes and their associated counters 170, 171. The spacings $d1$ and $d2$ 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:

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

as 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:

$$D2 = K - (d1' + d2') = m' + n'$$

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 subtraction of the commanded and signaled finish grinding stock removal $\Delta Rf$, the rough grinding stock removal $\Delta R$ is computed and signaled:

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

Whether all stock to be removed, $\Delta R$, is taken off in one continuous passing operation, or whether the two components $\Delta Rr$ and $\Delta Rf$ 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 infed 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 $\Delta R$ (or $\Delta Rr$, as the case may be), the passing is terminated. Preferably, the difference between the first and second signals equaling the quantity $\Delta R$ (or $\Delta Rr$) is found by presetting the rear gage body inwardly by the distance $\Delta R$ (or $\Delta Rr$) and then determining when the voltage E after any given pass has been restored to zero. In those cases where the thickness $\Delta R$ is removed by rough grinding passes, the remainder $\Delta Rf$ is thereafter removed by finish grinding passes, so that the end result of removing the thickness $\Delta R$ 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 N31 through N48 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. 15A-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 L1, L3 and L2 have been shown as supplying only to the circuits to all of the circuitry, various separate sources 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-G, 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. 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 these 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 circuits previously described with reference to FIGS. 10, 11, 12, 13 and 15A-G. The memory is also controlled by signals from a 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 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.

The system 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 reverse motor M17 and solenoid RS when the rear probe assembly is to be changed in its status, and control the front probe motor M50 and solenoid RS 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 operation and function 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 remachining 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 as my invention:

1. The method of machining a workpiece to have a surface contour which is symmetrical about a center point between first and second opposite edges spaced apart on the workpiece in the direction of one of a plurality of axes of relative motion between a tool and the workpiece, comprising the steps of bringing a workpiece sensor, which is relatively movable within
the tool along said one axis, into operative position relative to
the surface of the workpiece; initiating first relative motion of
the tool in one direction along said one axis and terminating
such motion in response to detection by said sensor of the first
ear edge of the tool; repeating second relative motion of the
tool in the opposite direction along said one axis and terminat-
ing such motion in response to detection by said sensor of the
second edge of the tool; measuring and signaling the distance
moved relatively by the tool in said opposite direction; initiating third relative motion of the tool in said one
direction along said one axis; utilizing said distance signaling
to terminate the third motion when the movement thereof is
equal to one-half the signaled distance; and thereafter numeri-
cally controlling plural axis relative motions of the tool ac-
cording to a contouring program prepared with a zero reference
point for said one axis midway between the two edges of the
workpiece.

2. The method of locating a reference point on a movable
tool carrier at the midpoint of a workpiece having first and
second edges spaced apart in the direction of a path along
which the carrier is linearly movable relative to the workpiece,
comprising the steps of bringing a tool sensor mounted at
the reference point on the carrier into operative position
adjacent the surface of the workpiece at any initial location
along said path, initiating relative motion of the carrier along
said path in one direction and terminating such motion in
response to detection by said sensor of the first edge of the
workpiece, initiating relative motion of the carrier along said
path in the opposite direction and terminating such motion in
response to detection by said sensor of the second edge of the
workpiece, measuring and signaling by digital electrical
signals the distance moved by the carrier in said opposite
direction; initiating relative motion of the carrier along said
path in said one direction, and utilizing said signals to ter-
minate the latter motion in said one direction when it becomes
equal to one-half the distance moved in said opposite
direction, whereupon the sensor and the reference point on
said carrier are located midway between the two edges of the
workpiece.

3. The method defined in claim 2, further including convert-
ing the digital signals representing distance moved in said op-
posite direction into second digital signals representing
one-half of such distance, measuring the distance moved dur-
ing the last motion in said one direction, and terminating such
last motion when the measured distance becomes equal to
the distance represented by said second digital signals.

4. The method of locating a reference point on a movable
tool carrier at the midpoint of a workpiece having first and
second edges spaced apart in the direction of a path along
which the carrier is linearly movable relative to the workpiece,
comprising the steps of advancing a sensing head on the carri-
er in a direction substantially normal to the workpiece surface
between said edges until two proximity switches on the head
are operatively disposed relative to the surface at any initial
location along said path, said proximity switches being usually
spaced in a direction parallel to said path on opposite sides of
said reference point, initiating first relative motion of said car-
rier in a first direction along said path and terminating such
motion when a first one of said proximity switches ceases

5. The method defined in claim 4 further characterized in
that said first motion is executed at a traverse velocity, said
second motion is executed at a creep velocity, said third
motion is executed at a traverse velocity, said fourth motion
is executed at a traverse velocity, and said fifth motion is ex-
ecuted at a traverse velocity.

6. The method defined in claim 4 further including convert-
ing the signals representing said net distance into second
signals representing one-half of said net distance, counting inc-
rements of movement while said fifth motion is being ex-
ecuted, and terminating said fifth motion when the total of
counted increments equals the distance represented by said
second signals.

7. In a machine tool adapted to receive a workpiece and
having a member movable along a linear path generally paral-
el to the surface of the workpiece between two edges of the
latter, the combination including a sensing head carried by
said member and movable relative to the latter in a direction
normal to said path, a proximity sensor carried by said sensing
head and movable with the latter to reside adjacent the work-
piece surface, means for registering and digitally signaling the
distances moved by said member along said path, first control
means for moving said head to locate the sensor in proximity
to said workpiece surface, second control means for moving
said member in one direction along the path until the work-
piece surface at one edge is no longer sensed by said sensor,
third control means for moving said member in the opposite
direction along the path until the workpiece surface at the
other edge is no longer sensed by the sensor, fourth control
means for registering in said registering means the distance
moved by the member under control of said third means, and
fifth control means for moving said member in said one
direction along the path through a distance equal to one-half
doing the distance previously registered and signaled in said re-
registering means.

8. The combination defined in claim 7 further characterized
in that said means for registering and signaling comprises a
pulse generator for producing a pulse for each increment
moved along the path by said member and a counter respon-
sive to said pulses, said fourth control means includes means
for supplying pulses from said generator to said counter, and
said fifth control means includes means for supplying pulses
from said generator to said counter and means controlled by
said counter for terminating the last movement in said one
direction when the pulses so supplied represent one-half of
the quantity registered in the counter under the control of said
fourth means.

9. The combination defined in claim 7 further characterized
by means for producing an initiation signal to start said first
control means, means responsive to completion of operation
by said first control means for starting operation of said sec-
cond control means, means responsive to completion of
operation of said second control means for enabling said
fourth control means and starting said third control means,
and means responsive to completion of operation of said third
control means for starting said fifth control means.

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