United States Patent [19]

Smith, Jr.

[11] **3,709,008**

[45] **Jan. 9, 1973**

[54] **GAUGE CONTROL METHOD AND APPARATUS FOR METAL ROLLING MILLS**

[75] Inventor: **Andrew W. Smith, Jr.,** Pittsburgh, Pa.

[73] Assignee: **Westinghouse Electric Corporation,** Pittsburgh, Pa.

[22] Filed: **Oct. 14, 1970**

[21] Appl. No.: **80,682**

[52] **U.S. Cl.** 72/8

[51] **Int. Cl.** **B21b 37/00**

[58] **Field of Search** 72/7–21, 28

[56] **References Cited**

UNITED STATES PATENTS

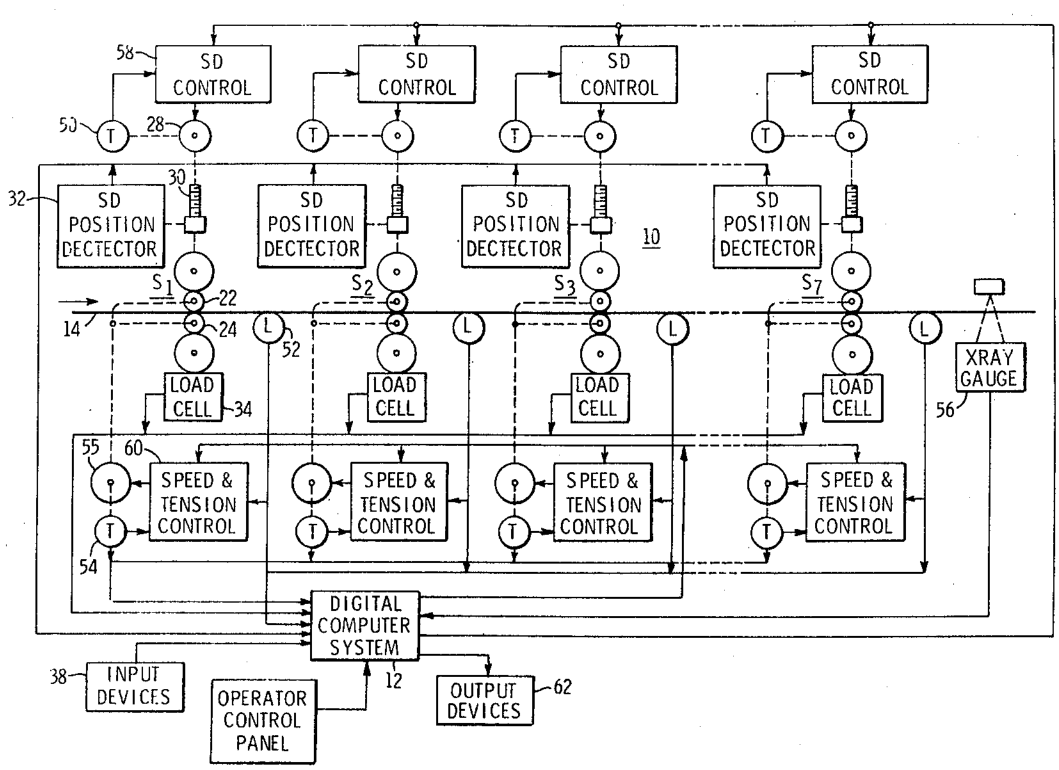
2,883,895	4/1959	Vossberg	72/9
3,355,918	12/1967	Wallace	72/8
3,357,217	12/1967	Wallace et al.	72/8
3,448,600	6/1969	Coleman et al.	72/8
3,553,991	1/1971	Chope	72/8

Primary Examiner—Milton S. Mehr
Attorney—F. H. Henson and R. G. Brodahl

[57] **ABSTRACT**

A programmed computer control system provides an on-line roll force gauge control for a multiple stand tandem hot metal strip rolling mill. A gauge control program calculates the workpiece strip delivery gauge error from at least one stand of the rolling mill and from this gauge error determines a required roll opening correction to remove this gauge error. The gauge control program then determines in relation to the magnitude of the delivery gauge error and related roll opening correction for the same one stand that this delivery gauge error is to be corrected by adjustment of the roll opening of that same one stand or is to be fed forward in the direction of the workpiece strip movement for correction in a succeeding stand of the rolling mill by adjustment of the roll opening of the succeeding stand. The roll opening correction is effective to adjust the latter stand operation for a time interval related to the movement of the workpiece strip increment from the stand where the gauge error is measured to the following correction stand of the rolling mill, assuming the latter stands are adjacent stands of the rolling mill.

26 Claims, 26 Drawing Figures



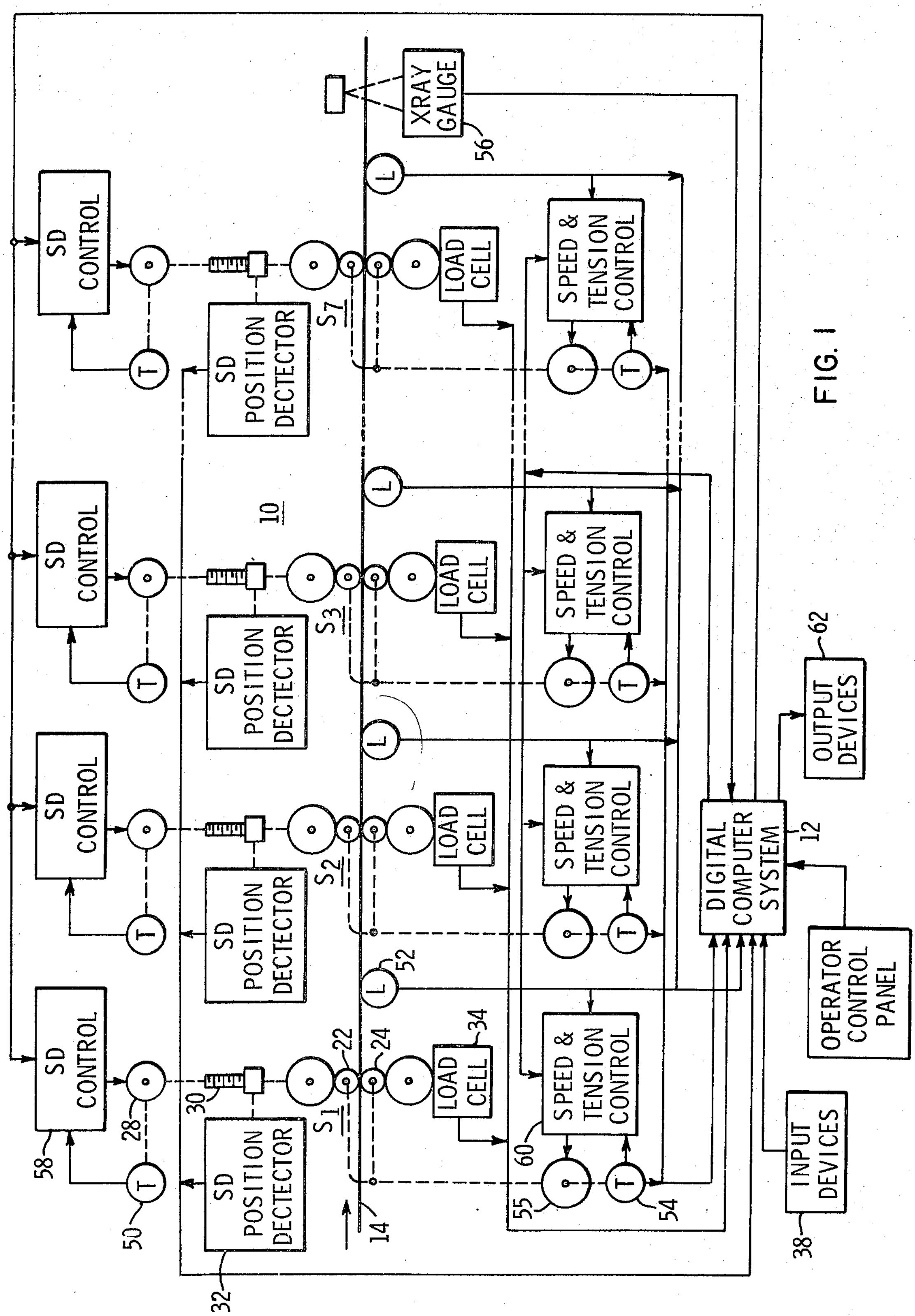

SD CONTROL
SD POSITION DECTECTOR
LOAD CELL
SPEED & TENSION CONTROL
XRAY GAUGE
DIGITAL COMPUTER SYSTEM
OUTPUT DEVICES
OPERATOR CONTROL PANEL
INPUT DEVICES
T
L
S1
S2
S3
S7
10
12
14
22
24
28
30
32
34
38
50
52
54
55
56
58
60
62

FIG. 1

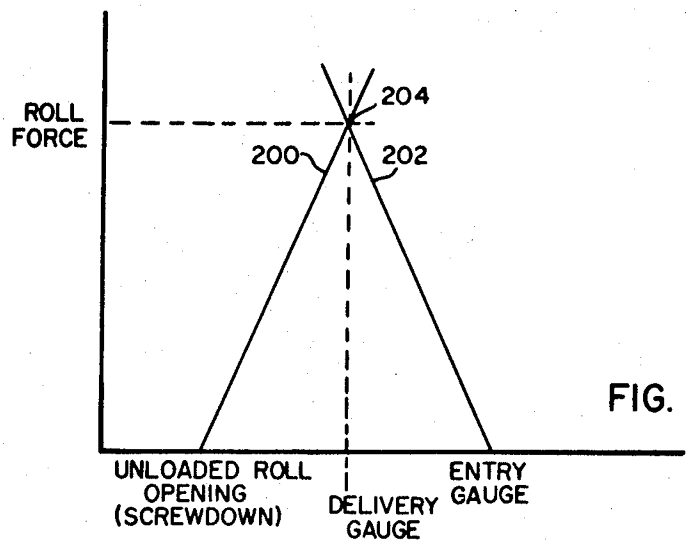


FIG. 2

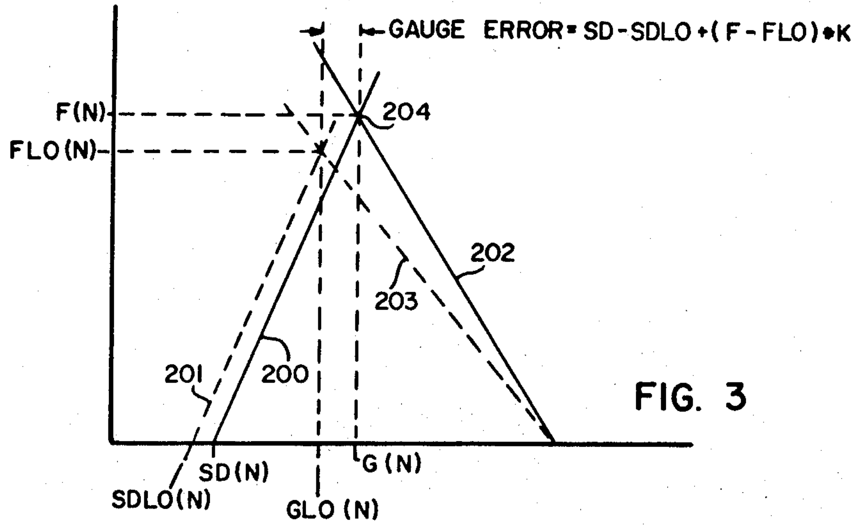


FIG. 3

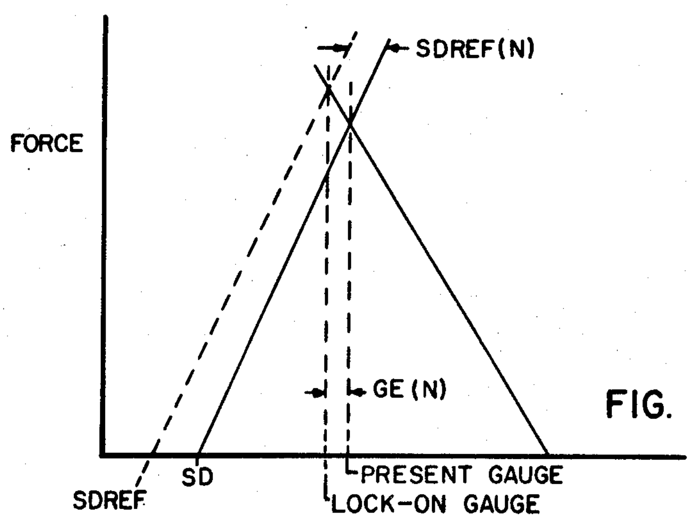


FIG. 4

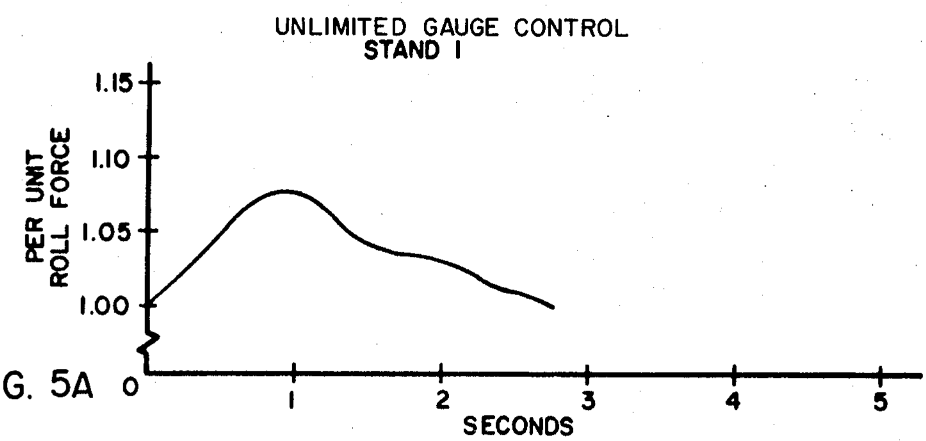


FIG. 5A

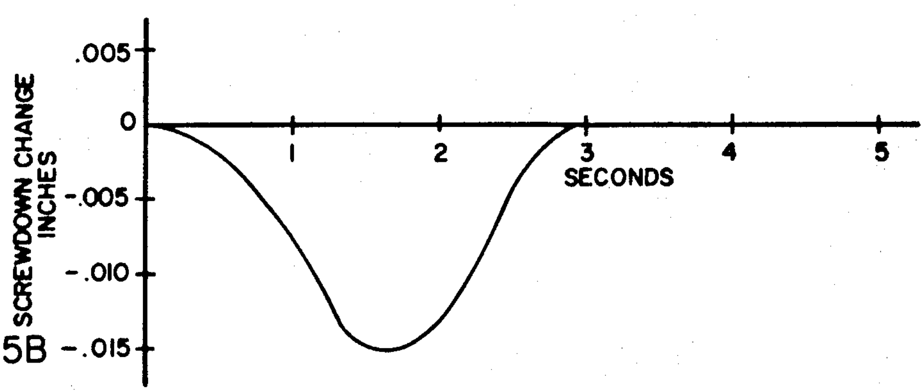


FIG. 5B

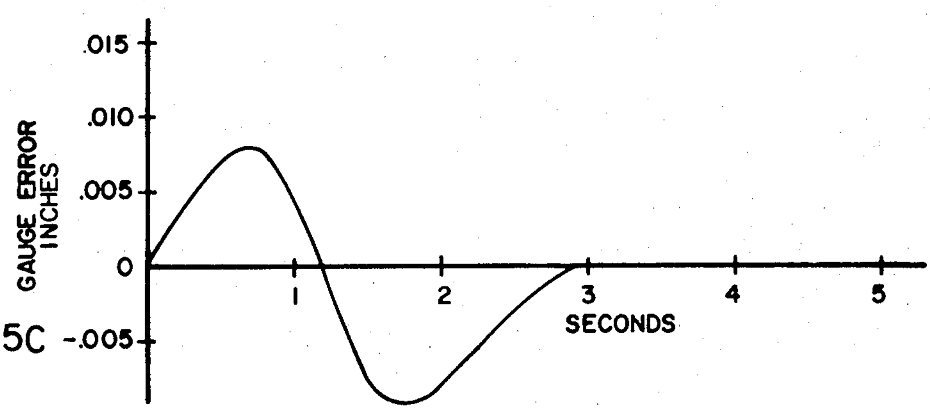


FIG. 5C

UNLIMITED GAUGE CONTROL
STAND 2

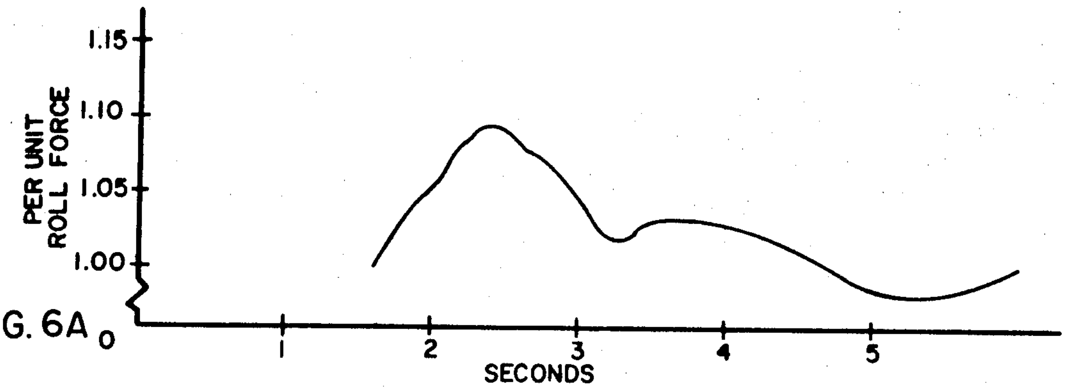


FIG. 6A

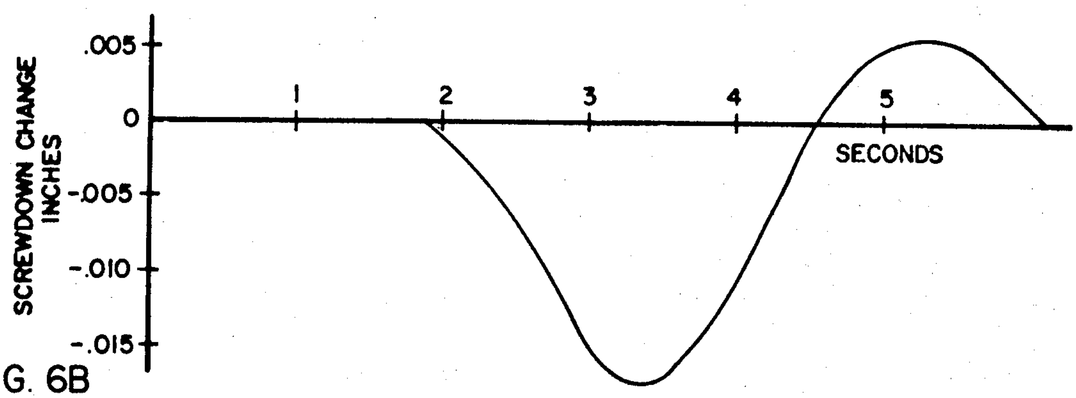


FIG. 6B

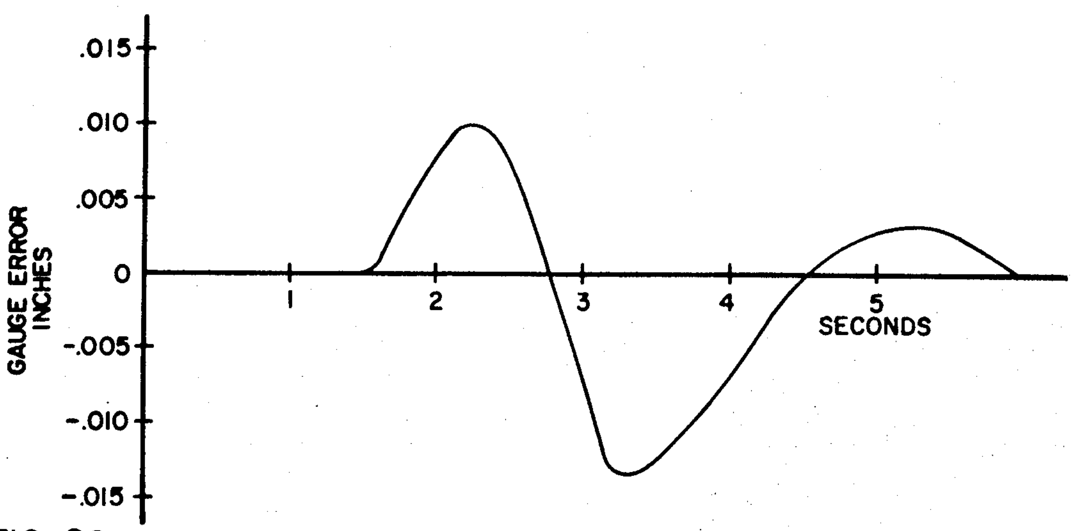


FIG. 6C

LIMITED GAUGE CONTROL
STAND I

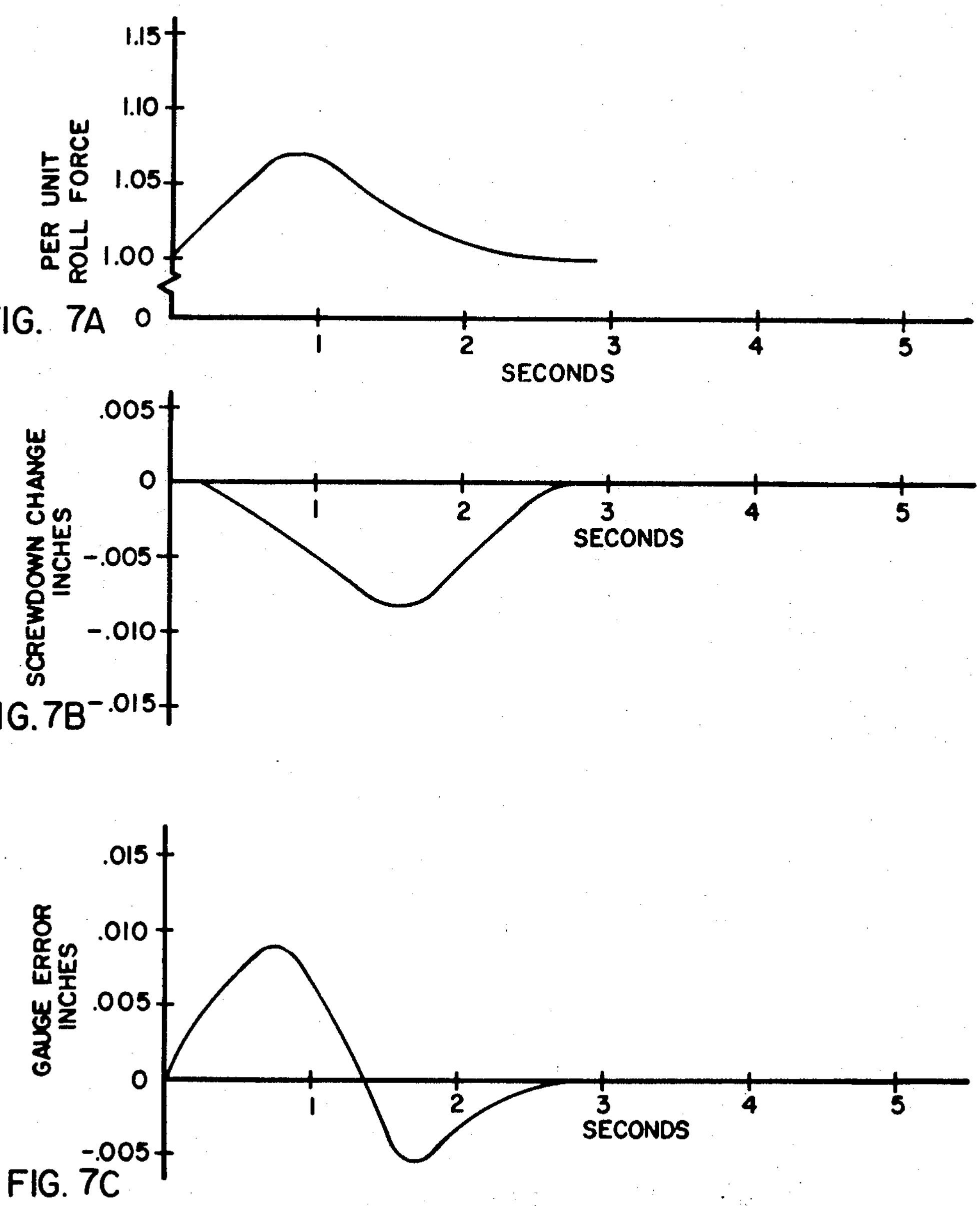


FIG. 7A

FIG. 7B

FIG. 7C

LIMITED GAUGE CONTROL
STAND 2

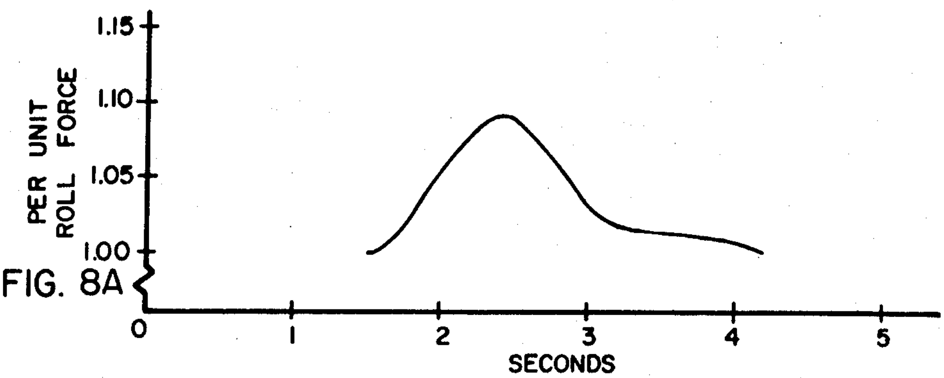


FIG. 8A

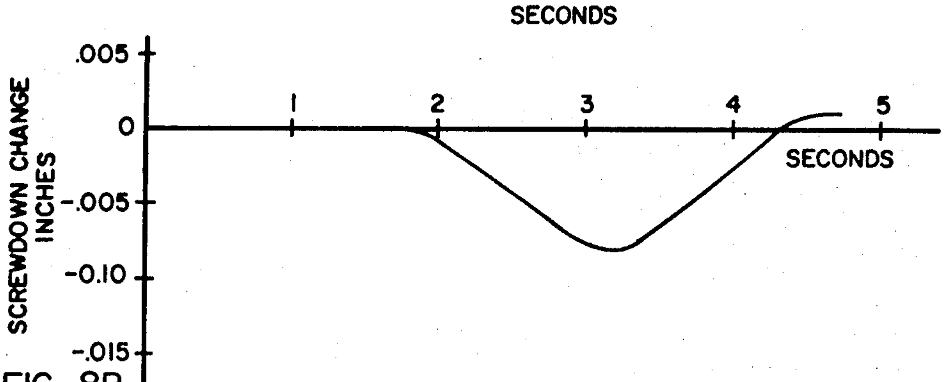


FIG. 8B

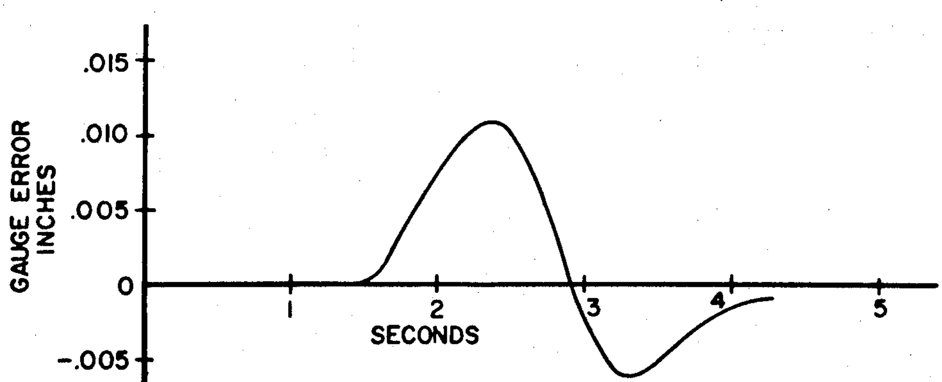


FIG. 8C

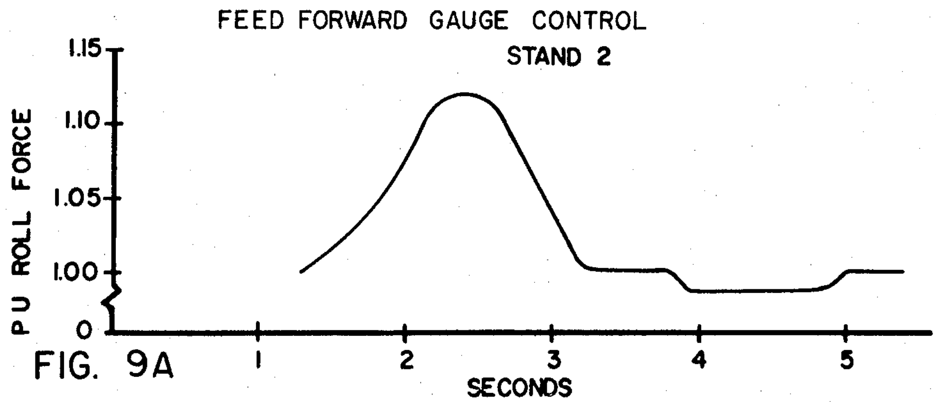


FIG. 9A

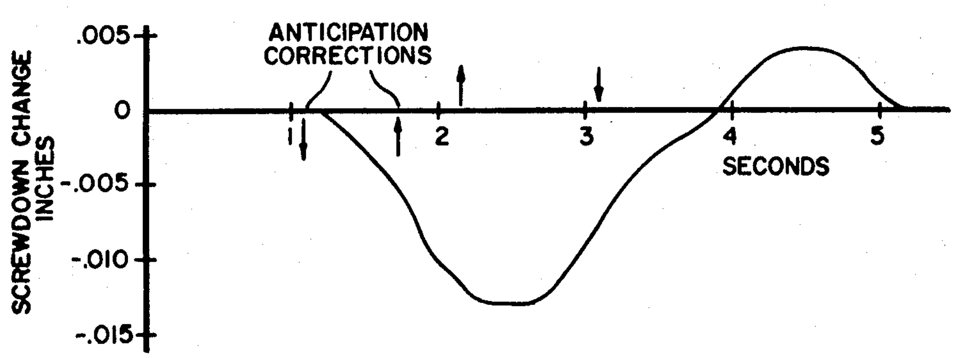


FIG. 9B

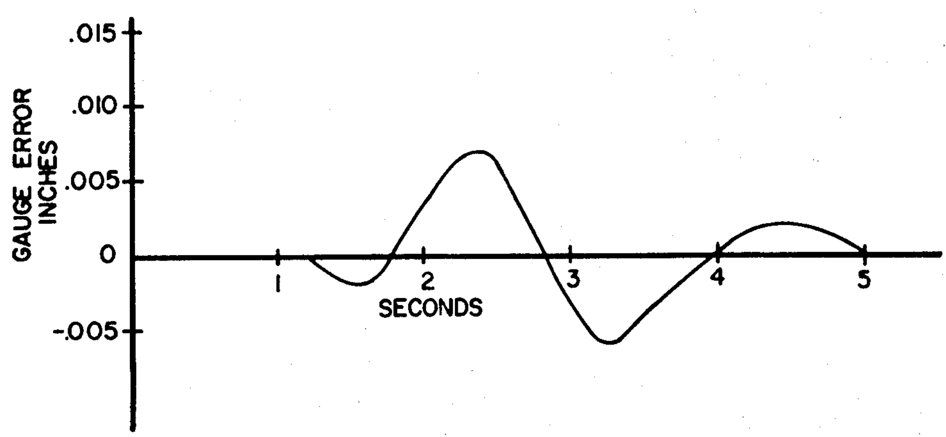


FIG. 9C

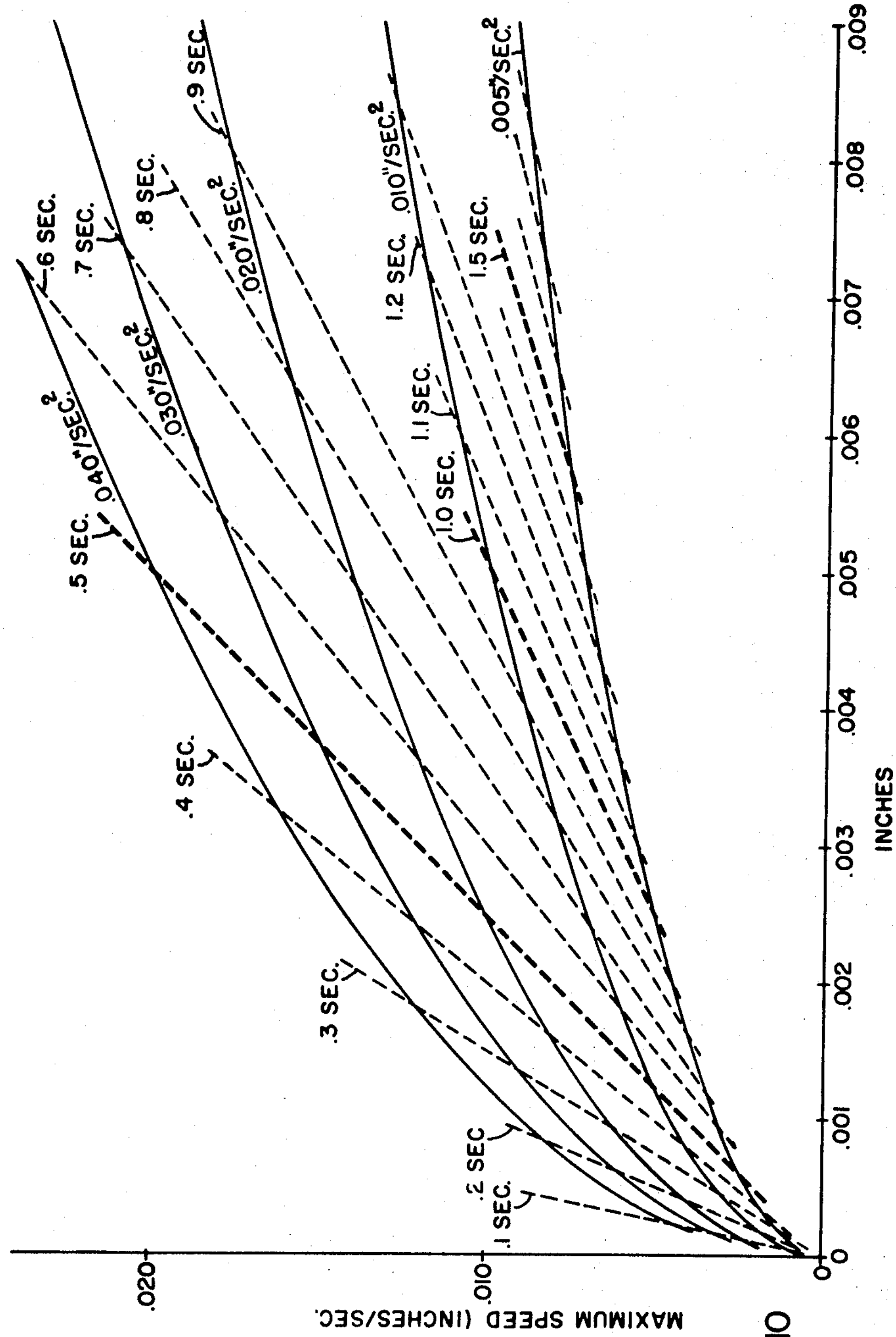

MAXIMUM SPEED (INCHES/SEC.
INCHES
.020
.010
0
.001
.002
.003
.004
.005
.006
.007
.008
.009
.1 SEC.
.2 SEC
.3 SEC.
.4 SEC.
.5 SEC.
.6 SEC.
.7 SEC.
.8 SEC.
.9 SEC.
1.0 SEC.
1.1 SEC.
1.2 SEC.
1.5 SEC.
.040"/SEC.2
.030"/SEC.2
.020"/SEC.2
.010"/SEC.2
.005"/SEC.2

FIG. 10

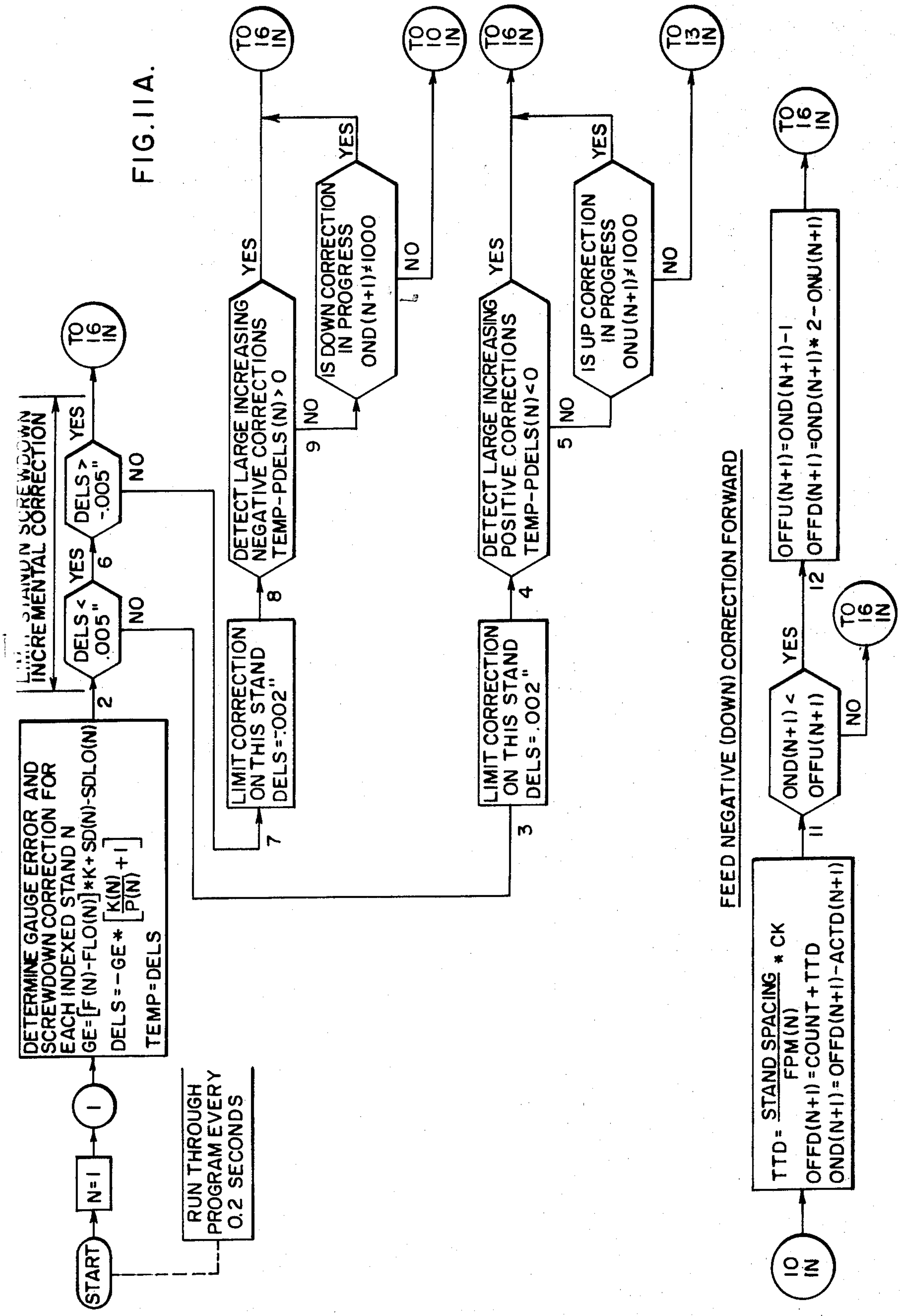

START
N=1
1
RUN THROUGH PROGRAM EVERY 0.2 SECONDS
DETERMINE GAUGE ERROR AND SCREWDOWN CORRECTION FOR EACH INDEXED STAND N
GE=[F(N)-FLO(N)]*K+SD(N)-SDLO(N)
DELS=-GE*[K(N)/P(N)+1]
TEMP=DELS
2
LIMIT STAND N SCREWDOWN INCREMENTAL CORRECTION
DELS< .005"
YES
NO
6
DELS> -.005"
YES
NO
TO 16 IN
7
LIMIT CORRECTION ON THIS STAND DELS=-.002"
8
DETECT LARGE INCREASING NEGATIVE CORRECTIONS TEMP-PDELS(N)>0
YES
NO
9
TO 16 IN
IS DOWN CORRECTION IN PROGRESS OND(N+1)≠1000
YES
NO
TO 10 IN
3
LIMIT CORRECTION ON THIS STAND DELS=.002"
4
DETECT LARGE INCREASING POSITIVE CORRECTIONS TEMP-PDELS(N)<0
YES
NO
5
TO 16 IN
IS UP CORRECTION IN PROGRESS ONU(N+1)≠1000
YES
NO
TO 13 IN
FEED NEGATIVE (DOWN) CORRECTION FORWARD
10 IN
TTD= STAND SPACING/FPM(N) * CK
OFFD(N+1)=COUNT+TTD
OND(N+1)=OFFD(N+1)-ACTD(N+1)
11
OND(N+1)< OFFU(N+1)
YES
NO
TO 16 IN
12
OFFU(N+1)=OND(N+1)-1
OFFD(N+1)=OND(N+1)*2-ONU(N+1)
TO 16 IN

FIG. 11A.

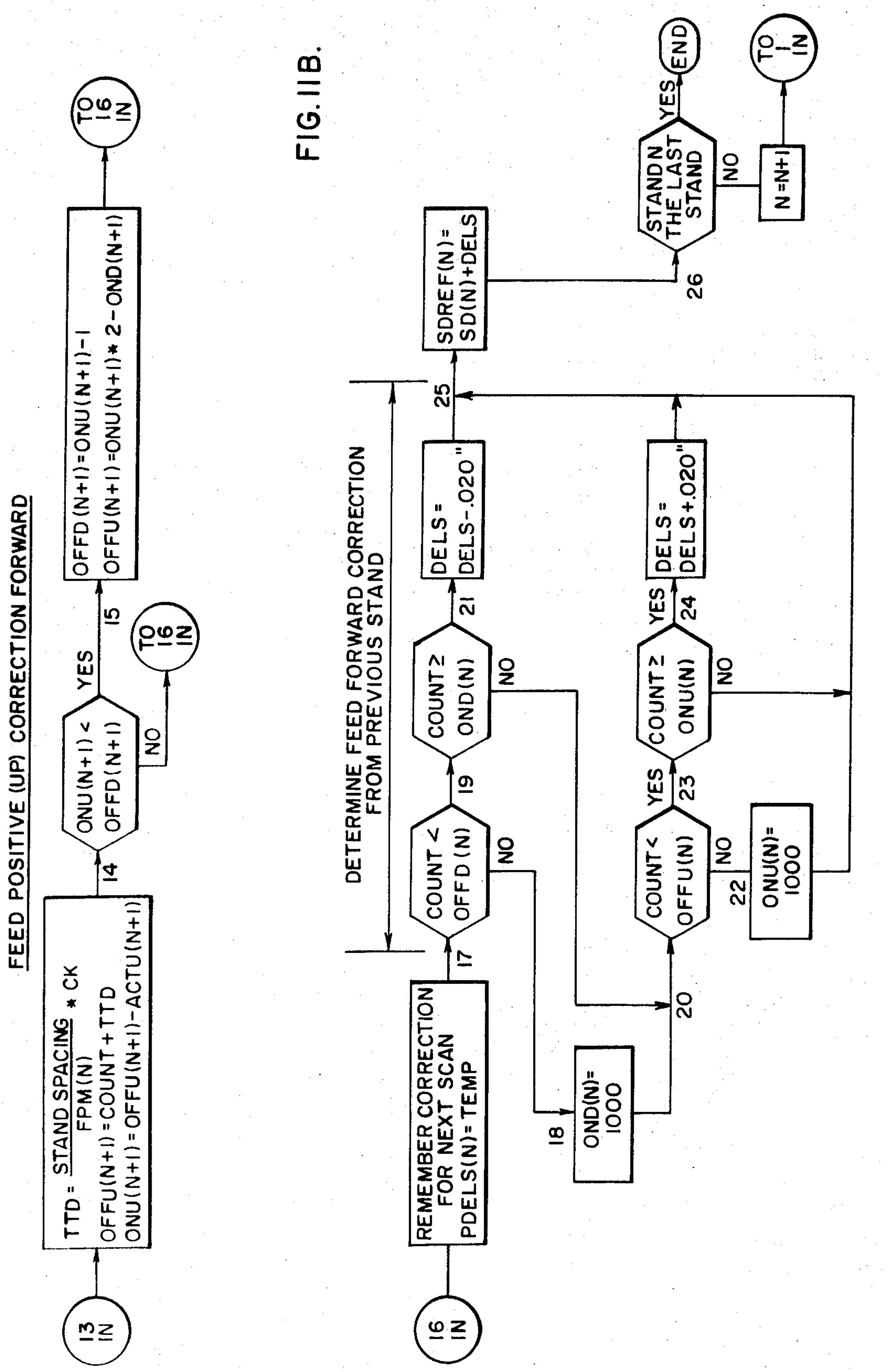

FEED POSITIVE (UP) CORRECTION FORWARD
13 IN
TTD = STAND SPACING / FPM(N) * CK
OFFU(N+1)=COUNT+TTD
ONU(N+1)=OFFU(N+1)-ACTU(N+1)
14
ONU(N+1) < OFFD(N+1)
YES
NO
TO 16 IN
15
OFFD(N+1)=ONU(N+1)-1
OFFU(N+1)=ONU(N+1)* 2-OND(N+1)
TO 16 IN
DETERMINE FEED FORWARD CORRECTION FROM PREVIOUS STAND
16 IN
REMEMBER CORRECTION FOR NEXT SCAN
PDELS(N)=TEMP
17
COUNT < OFFD(N)
NO
18
OND(N)= 1000
19
COUNT ≥ OND(N)
NO
20
21
DELS = DELS-.020"
COUNT < OFFU(N)
NO
22
ONU(N)= 1000
YES
23
COUNT ≥ ONU(N)
NO
YES
24
DELS = DELS+.020"
25
SDREF(N)= SD(N)+DELS
26
STAND N THE LAST STAND
YES
END
NO
N=N+1
TO 1 IN

FIG. 11B.

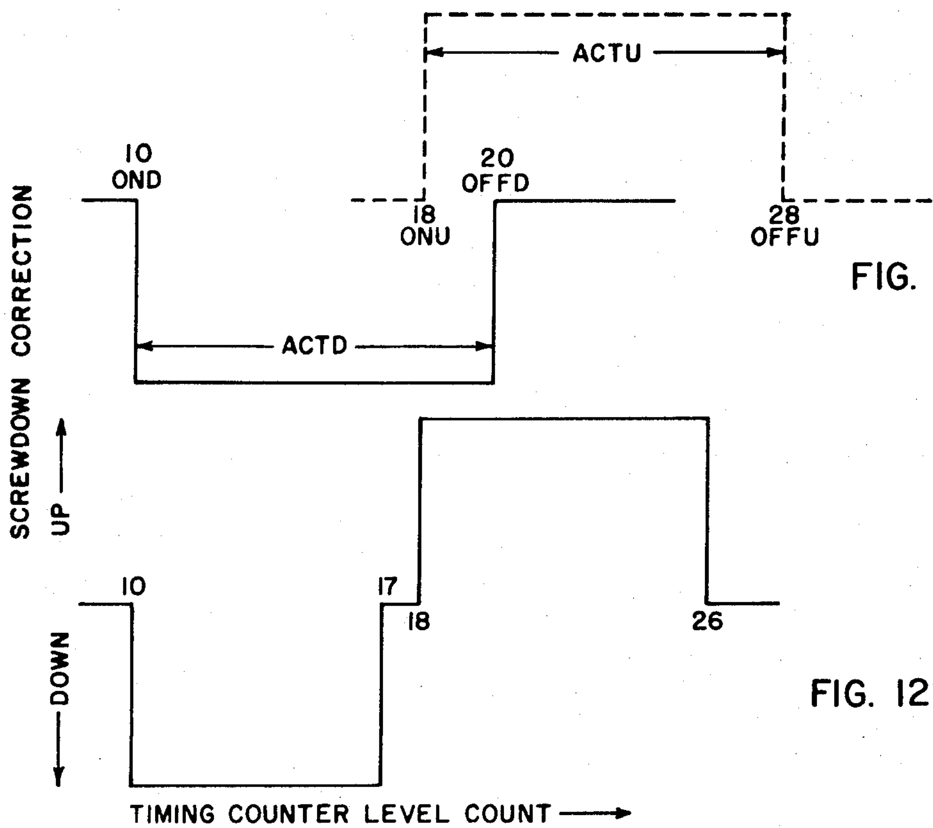


FIG. 12A

FIG. 12B

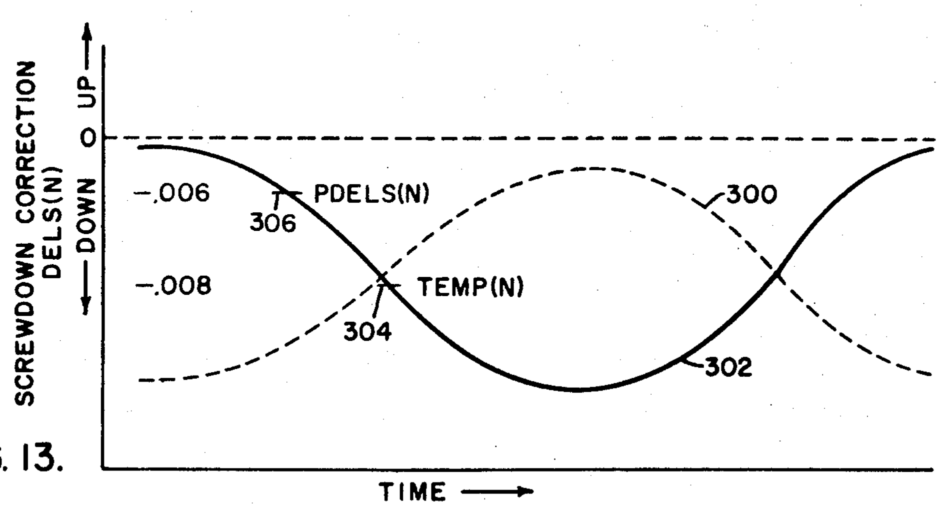


FIG. 13.

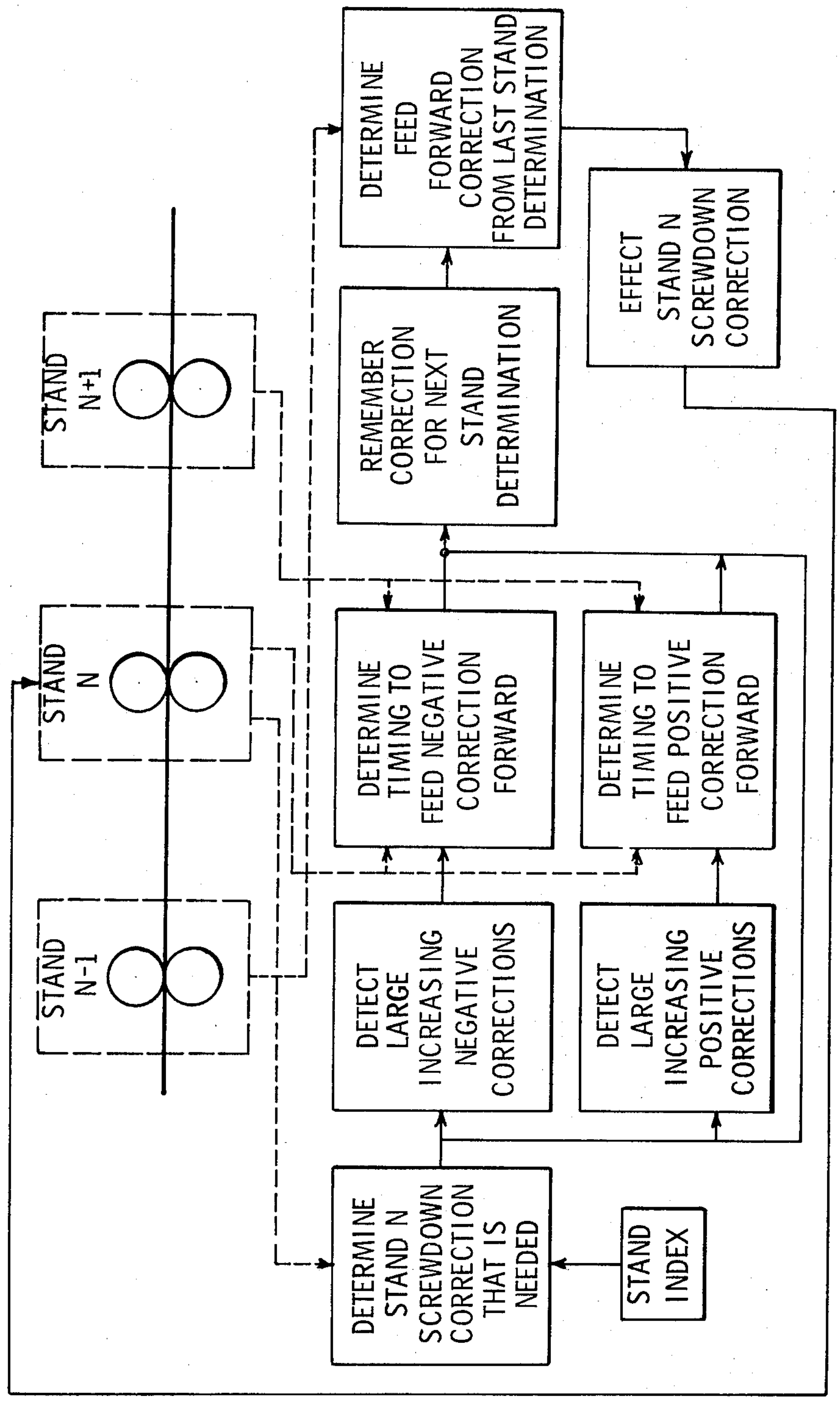

STAND N-1
STAND N
STAND N+1
DETERMINE STAND N SCREWDOWN CORRECTION THAT IS NEEDED
STAND INDEX
DETECT LARGE INCREASING NEGATIVE CORRECTIONS
DETECT LARGE INCREASING POSITIVE CORRECTIONS
DETERMINE TIMING TO FEED NEGATIVE CORRECTION FORWARD
DETERMINE TIMING TO FEED POSITIVE CORRECTION FORWARD
REMEMBER CORRECTION FOR NEXT STAND DETERMINATION
DETERMINE FEED FORWARD CORRECTION FROM LAST STAND DETERMINATION
EFFECT STAND N SCREWDOWN CORRECTION

FIG. 14

GAUGE CONTROL METHOD AND APPARATUS FOR METAL ROLLING MILLS

CROSS REFERENCE TO RELATED APPLICATIONS

Reference is made to the following copending Pat. applications: Ser. No. 686,783, filed Nov. 29, 1967, now issued as U.S. Pat. No. 3,561,237 and entitled "-Predictive Roll Force Gauge Control Method and Apparatus for Metal Rolling Mills" by C. W. Eggers and J. Csonka: Ser. No. 80,683, filed Oct. 14, 1970, and entitled "Gauge Control Method and Apparatus for Metal Rolling Mills" by E. J. Masar.

BACKGROUND OF THE INVENTION

The present invention relates to metal rolling mills and more particularly to roll force gauge control systems and methods used in operating such mills.

In the operation of a metal or steel reversing or tandem rolling mill, the unloaded roll opening and the speed at each tandem mill stand or for each reversing mill pass are set up by an operator or by a programmed digital computer control system to produce successive workpiece reductions resulting in delivered work product at the desired gauge. Generally the loaded roll opening at a given roll stand equals the stand delivery gauge or thickness on the assumption that there is little or no elastic workpiece recovery.

Since the set up conditions can be in error and since certain mill parameters affect the stand loaded roll opening during actual rolling operation and after set up conditions have been established, a stand gauge control system is usually employed to closely control the stand delivery gauge. At the present state of the rolling mill art, and particularly the steel rolling mill art, a stand gauge control system is normally used for a reversing mill stand and for predetermined stands in tandem rolling mills.

The well known gaugemeter or roll force gauge control system has been widely used to produce stand gauge control in metal rolling mills and particularly in tandem hot steel strip rolling mills and reversing plate mills where experience has demonstrated that roll force control is particularly effective. This system uses the roll force signal from individual stand load cells as an indication of gauge variation, and signals the stand screw down or roll opening control apparatus to correct for the delivery gauge error from each roll force controlled stand. The roll force signal does not provide a measure of the actual delivery gauge from a given stand but only indicates the change in gauge from an initial value. Therefore, a workpiece thickness measurement gauge such as the well known X-ray gauge, is generally used to maintain calibration of the roll force system, and this is done through a monitoring system with the X-ray gauge positioned subsequent to the last stand of the tandem rolling mill and providing a periodic check to correct the roll force system calibration.

The automatic gauge control system on each roll stand is energized as the work strip enters the roll bite. It is necessary to establish a roll force reference value to control the delivery strip thickness from the stand. This reference value can be set by locking on the head end value of the work strip gauge or can be set by a digital control computer system. The roll force system on a given stand will then operate to maintain the workpiece delivery gauge or thickness obtained with that roll force value unless modified by the X-ray gauge monitor system.

It was known in the prior art to provide a slave roll force gauge control system, wherein the screws on a given rolling mill stand move in response to the roll force change of a previous mill stand rather than by the roll force change on the same mill stand. The screw down of the following slave stand can follow the roll force error or a signal representing screw movement on the previous roll stand.

A more detailed description of roll force automatic gauge control systems can be found in an article published in the Iron and Steel Engineer for December 1967 at pages 75 through 86 and entitled "Automatic Gauge Control for Modern Hot Strip Mills" by J. W. Wallace.

A more detailed description of computer programming techniques in relation to the control of metal rolling mills can be found in an article in the Iron and Steel Engineer Yearbook for 1966 at pages 328 through 334 entitled "Computer Program Organization for an Automatically Controlled Rolling Mill" by John S. Deliyannides and A. H. Green, and in another article in the Westinghouse Engineer for January 1965 at pages 13 through 19 and entitled "Programming for Process Control" by P. E. Lego.

The U.S. Pat. No. 3,357,217 of J. W. Wallace discloses the utilization of one or more succeeding stands after a gauge error measurement stand, with those succeeding stands being operative as slave stands to provide gauge error correction for detected but uncorrected off gauge work strip leaving the previous measurement stand end. This practice was known to be desirable for rapid changes in gauge error such as resulted from localized thermal condition differences along the length of the workpiece due to furnace skid marks. Gain tuning of the master or measurement stand *N* is provided at some conservative value such as 80 percent of the gauge error signal for reasons of stability, and then a slave stand error correction signal is transmitted to a subsequent correction stand *N*+1 in a proportion of 20 percent or 30 percent of the gauge error signal relative to the master stand *N* gauge error signal. In this way the work strip gauge error not corrected at the master stand *N* is substantially corrected at the following slave stand *N*+1. This was a continuously operative analog roll force gauge control system responsive to the gauge error signal detected at master stand *N*.

The roll force gauge control slave system disclosed in U.S. Pat. No. 3,357,217 did not include a roll force feedback gauge control system on the correction stand *N*+1, so the only gauge error signal applied to this correction stand *N*+1 was the feed forward gauge error signal from the previous measurement stand *N*. There is a problem of error grow back at correction stand *N*+1 for a succeeding stand error correction without its own gauge control loop, and if an overcorrection in the prior stand *N* is attempted an unstable condition can arise when the stand *N* correction might run away. The gauge error measured at stand *N* was continuously applied for adjusting the roll opening of stand *N* and adjusting the roll opening of the following slave stand *N*+1.

In the operation of a tandem hot strip rolling mill having a plurality of roll stands, a typical work strip will enter the first stand having a thickness of about 1 inch and be successively reduced in passing through the plural roll stands to a final last stand delivery thickness of about 0.1 inch. The entry speed into the first stand is typically in the order of 200 feet per minute, and the delivery speed leaving the last stand can be in the order of 2,000 feet per minute. Relative to the first roll stand there is no previous measurement roll stand for which the gauge error can be sensed and a corresponding gauge error correction signal developed. Relative to the last stand the delivery speed of 2,000 feet per minute is generally too fast to provide a reasonable transport time from the next previous roll stand for making the desired gauge error correction. A typical transport time interval for a given work strip portion to travel about 18 feet from the second roll stand to the third roll stand is in the order of 2 seconds. With each of the respective stands being spaced about 18 feet from the next adjacent roll stand, it should be readily apparent that the transport time interval of a given work strip increment between adjacent stands is greatest between the first and second roll stands and then progressively decreases in time interval between each successive pair of adjacent roll stands.

SUMMARY OF THE PRESENT INVENTION

The present invention determines a gauge error related screwdown correction in accordance with a sensed work strip gauge error at a selected measurement stand *N* and feeds that determined gauge error screwdown correction forward in the direction of strip travel to a succeeding stand, such as the next adjacent stand *N*+1, and applies the screwdown correction for a determined time duration to adjust the operation of that succeeding stand N+1 for correcting the gauge error sensed at the previous measurement stand *N*. This determined time duration is established in relation to the magnitude of screwdown correction in stand *N* used to initiate such corrections in the *N*+1 stand and the speed of the screwdown system. Once the portion of the strip requiring a large correction has reached the next stand, the feed forward correction is no longer needed. This screwdown correction is fed forward to the next succeeding stand *N*+1, for the time duration determined by the control program, with the ON beginning and OFF termination of that time duration being determined, after which the screwdown correction is removed from the control of the succeeding stand *N*+1. For example, if the gauge error is sensed at measurement stand *N*, the transport time is the time interval required for a given portion of the work strip to travel from that measurement stand *N* to the next succeeding correction stand *N*+1. After this time duration or time interval, the screwdown correction fed forward from stand *N* no longer is needed to control the operation of the succeeding correction stand *N*+1 since the gauge error detected at stand *N* is now sensed in stand *N*+1.

The present control system is operative to sense gauge error at the roll bite at a measurement roll stand *N*. For a typical hot strip mill there are no intermediate X-ray gauges between the early roll stands to sense the actual delivery gauge of the work strip leaving one of these early roll stands. Thusly, the previous stand *N* is in effect used as a delivery gauge measurement device and the screwdown correction to remove the measured work strip gauge error, when greater than a predetermined limit value, is passed forward to control the operation of a succeeding correction stand *N*+1. When the measured gauge error for stand *N* cannot be corrected by a suitable adjustment of stand *N* for reasons of the size of the correction needed and the necessary time required to correct such a large gauge error by stand *N*, this gauge error is fed forward in anticipation of the work strip increment containing the sensed gauge error arriving at the next successive roll stand.

It should be understood that the gauge error measured at stand *N* determines the screwdown correction which is applied in full to correct the operation of stand *N* in the usual roll force automatic gauge control approach relative to stand *N*. In addition the full screwdown correction is also applied to the following slave stand *N*+1 for a determined time duration. The correction stand corresponding to the work strip gauge error measured at stand N is passed through effective dead band limits, such that a predetermined minimum gauge error must occur before an error correction signal is applied to the following stand *N*+1.

For each roll stand there is usually provided a feedback roll force gauge control system. For example, stand *N* has its own roll force feedback gauge control loop, and the following stand *N*+1 has its own roll force feedback gauge control loop. The gauge error measured at stand *N* is fed forward to stand *N*+1, if the gauge error is greater than the minimum error limit. Thusly stand N+1 has its own feedback gauge error signal, as well as the feed forward gauge error signal from previous measurement stand *N*. Both of these error signals are additively applied to correct gauge error at the correction stand *N*+1.

If the *N*+1 stand does not have a roll force gauge control system, this feed forward correction is still applicable. The screwdown system on the *N*+1 stand would be run in the appropriate direction for the controlled length of time.

The measurement stand *N* has an inherent response time characteristic which prevents an instantaneous correction at measurement stand *N* for the gauge error measured at stand N. For this reason the gauge error, when greater than a provided limit value, is fed forward to the following correction stand *N*+1 to allow the latter stand *N*+1 to in effect have a longer available time to respond to the gauge error measured at previous stand *N*.

The present control system locks in on the determined screwdown correction to remove the gauged error for a time interval determined by the decrementing of a signal counter provided within the control system and in relation to the physical travel of the gauge error containing work strip increment from the measurement stand *N* to the correction stand *N*+1. The present control system then again locks in on the next determined screwdown correction for the gauge error at measurement stand *N* and the same gauge error correction operation is repeated successively as necessary in accordance with the sensing of a gauge error at measurement stand *N* greater than the provided dead band signal limits.

The roll force gauge control response speed for a given roll stand depends principally on the system gain of the roll force gauge control, that is the rate of control screwdown movement per unit of detected roll force error. Since the stand delivery gauge is determined by the intersection point of the mill spring curve (roll force versus roll opening) and the workpiece deformation curve (yield force versus thickness reduction), the total amount of the screwdown movement required to correct a roll force error and the associated workpiece gauge error depends primarily on the mill spring modulus and the workpiece plasticity. The workpiece plasticity and the mill spring modulus thus affect the rate at which screwdown corrective control actions should be applied which is the system gain.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of a tandem hot strip metal rolling mill and a digital computer system operative for operational control of the rolling mill, including workpiece gauge control, and arranged in accordance with the principles of the present invention;

FIG. 2 illustrates a typical spring curve and workpiece deformation curve relationship;

FIG. 3 illustrates the operation of a roll force gauge error detection system;

FIG. 4 illustrates the determination of a screwdown correction to remove the gauge error at a roll stand N;

FIGS. 5A, 5B and 5C illustrates the response of a gauge control system of the first roll stand as a skid mark in the workpiece is passing through that first roll stand;

FIGS. 6A, 6B and 6C illustrates the operation of the gauge control system of the second roll stand when this same skid mark passes through the second roll stand;

FIGS. 7A, 7B and 7C illustrates the operation of a limited gauge control for the first roll stand for this same skid mark condition;

FIGS. 8A, 8B and 8C illustrates the operation of a limited gauge control for the second roll stand for this same skid mark condition;

FIGS. 9A, 9B and 9C illustrates the gauge error correction resulting from a feed forward of the determined screwdown correction relative to a workpiece gauge error detected at the first roll stand to control the operation of the succeeding second roll stand;

FIG. 10 illustrates the roll opening adjustment characteristics of a typical screwdown controlled roll stand;

FIGS. 11A and 11B illustrates the gauge control program logic flow chart in accordance with the present invention;

FIGS. 12A and 12B illustrates the technique used to modify an overlap of a DOWN screwdown correction followed by an UP screwdown correction to avoid such an overlap in the control operation;

FIG. 13 illustrates the determination that an increasing negative screwdown correction is taking place such as is the operation at program step 8 in the program flow chart; and

FIG. 14 shows a functional block diagram to illustrate the operation of the present gauge control system.

DESCRIPTION OF THE PREFERRED EMBODIMENT

There is shown in FIG. 1 the tandem hot strip steel finishing mill 10 operated with improved gauge control performance by a digital computer system 12 in accordance with the principles of the present invention. Generally however the invention is applicable to various types of mills in which roll force gauge control is employed. For example the invention can be suitably adapted for application in hot steel plate reversing and other rolling mills.

The tandem mill 10 includes a series of reduction rolling stands S1 through S7 with only four of the stands S1, S2, S3 and S7 shown. A workpiece 14 enters the mill 10 at the entry end in the form of a bar and it is elongated as it is transported through the successive stands S1 through S7 to the delivery end of the mill where it is coiled as a strip on a down coiler. The entry bar would be of known steel grade and it typically would have a thickness of about 1 inch and a width within some limited range such as 20 inches to 80 inches. The delivered strip would usually have approximately the same width and a delivery gauge or thickness based upon the production order for which it is intended. In the reduction rolling process the successive stands operate at successively higher speeds to maintain proper workpiece flow. Each stand produces the predetermined reduction or draft such that the total mill draft reduces the entry bar to final delivery strip with the desired gauge. Each stand is conventionally provided with a pair of work rolls 22 and 24 between which the workpiece 14 is passed. The large DC drive motor 25 is controllably energized at each stand to drive the corresponding work rolls at a predetermined speed.

As previously described the sum of the unloaded work roll opening and the mill stretch substantially defines the workpiece gauge delivered from any particular stand in accordance with Hooke's law. To vary the unloaded work roll opening at each stand a pair of screwdown motors 28 with only one being shown in FIG. 1 at each stand position respective screwdowns 30 which clamp against opposite ends of the backup rolls and thereby apply pressure to the work rolls 22 and 24. Normally the two screwdowns 30 at a particular stand would be in identical positions but they can be located at different positions for strip guidance during threading or for other purposes. It should be noted that the provision of an electric motor driving a screwdown mechanism 30 to control the stand roll opening can be replaced by a hydraulic positioning servo system or a hydraulic motor operative with a screwdown mechanism if desired.

A conventional screwdown position detector 32 provides an electrical signal representation of the screwdown controlled roll opening position at each roll stand. To provide an absolute correspondence between the screwdown position and the unload roll opening between the associated work rolls a screwdown position detection system which includes the screwdown position detector 32 can be calibrated from time to time as desired.

Roll force detection is provided at each of predetermined stands by a conventional load cell 34 and in many cases stands without roll force gauge control would also be equipped with such load cells. The number of stands to which roll force gauge control is applied is predetermined during the mill design in accordance with cost and performance standards, and increasingly there is a tendency at the present time to apply roll force gauge control to all of the stands in a tandem hot strip steel mill. In the illustration in FIG. 1 a roll force gauge control system is employed at each of the seven stands S1 through S7.

The digital computer system **12** can provide automatic control for the operation of the tandem mill **10** as well as desired preceding production processes not illustrated, such as the operation of a roughing mill. Preferably the digital computer system comprises a programmed process control digital computer which is interfaced with the various mill sensors and the various mill control devices to provide control over many of the various functions involved in operating the tandem mill **10**. According to the user preference, the computer **12** can also include conventional manual and/or automatic analog controls for backup operation in performing preselected mill functions. The digital computer system **12** can include a central integrated process control or set up processor with associated input/output equipment, such as that included in the computer system known as the Prodac 2000 (P-2000) currently sold by the Westinghouse Electric Corporation. The P-2000 processor typically uses an integral magnetic core 20,000 word (16 bit) memory with nominal 3.0 microsecond cycle time.

The computer processor is associated with predetermined input systems not specifically illustrated which typically can include a conventional contact closure input system to scan contact or other signals representing the status of various process conditions, a conventional analog input system which scans and converts process analog signals, an operator controlled and other information input devices **38** such as paper tape, teletypewriters and dial input devices. It is noted that the input devices **38** are indicated by a single block in FIG. 1 although different input devices can and typically would be associated with the one or more digital computers in the digital computer system **12**. Various kinds of input information are entered into the digital computer system **12** through the input devices **38** including for example desired strip delivery gauge from the rolling mill and workpiece temperature, workpiece strip entry gauge and width by entry detectors if desired, grade of steel being rolled, any selected workpiece plasticity tables, hardware oriented programs and control programs for the programming system, and so forth.

The contact closure input system and the analog input system interface the digital computer system **12** with the process through the medium of measured or detected variables. The present invention is largely involved in the functioning of the automatic gauge control computer system hereinafter referred to as the AGC computer. In a typical invention application various mill signals are applied to the AGC computer input system. These mill signals include the following: (1) a roll force signal from the load cell **34** and each of roll stands S1 through S7 proportional to the respective stand roll separating force for use in predictive feed forward roll force gauge control; (2) 14 bit screwdown position signals generated by the respective screwdown position detectors **32** at the stands S1 through S7 for use in predictive feed forward roll force gauge control; (3) position signals from respective loopers **52** for use in looper tension control; (4) stand speed signals generated by respective tachometers **54** with the stand S7 speed signal and/or other stand speed signal being used for calculation of the stand mass flow speed relationships for the X-ray gauge monitor operation; (5) a gauge deviation signal from the X-ray gauge **56** at the delivery end of the mill for programmed monitoring gauge control through the predictive roll force control; (6) an entry temperature signal from a mill entry temperature detector (not shown); if references are provided by the set up computer operation, the mill entry temperature for a first workpiece is stored and screwdown compensation is made for subsequent workpieces if the temperature difference of those subsequent workpieces is determined from the stored reference value; (7) workpiece width signals supplied by side guard follow potentiometers (not shown) for mill spring constant calculations, and so forth.

The measured head end roll force at each roll stand can be stored and used as a reference for roll force gauge controlled functioning at the respective stands if the AGC computer is in the lock on mode of roll force operation. On the other hand if the AGC computer is in the absolute mode of roll force operation, the set up computer operation calculates a predicted head end roll force at each stand which is used as an absolute reference for roll force gauge control functioning. Various process data input signals are coupled to the AGC computer through the contact closure input system and can include a strip in stand signal based on the load cell outputs which enable the roll force gauge controls to function. A contact closure output system would normally be associated with the digital computer system **12**. In this instance contact closure output systems are respectively associated with the various control devices operated in response to control actions calculated or determined by execution of the control programs in the AGC computer. To effect determined control actions control devices are operated directly by means of output system contact closures or by means of analog signals derived from output system contact closures through a digital to analog converter. The principal control action outputs from the AGC computer contact closure output system includes screwdown positioning system commands which are applied to respective screwdown controls **58** in operating the screwdown motors **28** for the screwdown movement, and speed anticipate signals which are applied to various looper tension control systems to cause a change in drive speed to compensate for a change in thickness being made by a screwdown movement. Display and printout systems here illustrated as output devices **62** such as a numerical display tape or teletypewriter systems are also associated with the outputs of the digital computer system **12** in order to keep the mill operator generally informed about the mill operation, and in order to signal the operator regarding an event or alarm condition which may require some action on his part. The printout systems are also used to log mill data according to computer log program direction.

A multi-stand, continuous, hot strip rolling mill at the present time employs a roll force gauge control system to maintain desired delivery workpiece gauge. Typically a hot strip rolling mill will roll a single workpiece strip simultaneously in all of its stands. Therefore the workpiece gauge control system used with the rolling mill should be able to detect gauge errors in the workpiece strip as quickly as possible, and the gauge control system should be able to make appropriate roll opening corrections in as many roll stands as may be necessary. The two workpiece gauge error detection systems most commonly used at the present time are the X-ray and the roll force systems. X-ray gauge devices could in theory be placed between each stand; they are accurate, but they are rather expensive to provide in this manner and difficult to maintain, and can only detect errors after the workpiece strip has left a previous given roll stand. On the other hand, the roll force gauge error detection system is much less expensive to provide, and can be more easily implemented for operation with all the roll stands; it detects errors in delivery gauge from a given roll stand as the workpiece strip is positioned between the rolls of that roll stand and thereby permits immediate evaluation of desired corrections to the roll openings of the same stand and succeeding stands. Unfortunately, the roll force gauge error detection system provides only a relative evaluation of the workpiece delivery gauge, it typically measures how much the delivery gauge leaving a given stand has deviated from the gauge of the head end portion of the workpiece strip.

A practical combination of the two gauge error detection systems is to use roll force error feedback information to calculate fast roll opening corrections to correct the sensed fluctuations in gauge, and to use one X-ray gauge device positioned after the last roll stand to evaluate the absolute gauge or thickness of the workpiece strip coming out of the last roll stand. The fast roll opening corrections are calculated from the roll force error feedback information to indicate the change in stand roll force ΔF, combined with the stand screwdown position change ΔSD and the known mill spring modulus K of the rolling stand, in accordance with the well known relationship

$$\Delta H = \Delta F(K) + \Delta SD \qquad 1$$

The slower X-ray gauge device evaluation is used to calculate simultaneous roll opening corrections to monitor the operation of several roll force gauge controlled stands so that the absolute value of the workpiece gauge leaving each such roll stand can be brought to the desired value.

The output of both of these workpiece gauge error detection systems are respective changes in the positions of the screwdowns controlling the roll opening of the respective stands.

FIG. 2 shows the linear approximations of the mill spring deflection as shown by curve **200** and the workpiece product deformation as shown by curve **202** in a typical rolling mill stand. The unloaded roll opening SD, sometimes called the screwdown because of the screw and nut system that can be used for adjusting the roll opening, is the same as the workpiece delivery gauge that would be delivered if there were no roll separating force. As the roll force increases with a constant roll opening position setting, the workpiece delivery gauge increases, since the mill stand stretches or deflects. This is shown by the curve **200** with slope $1/k$, where the mill spring modulus

$$K = \Delta SD/F \qquad 2.$$

The product deformation or plasticity characteristic P is represented by the curve **202** with slope $1/P$, where workpiece plasticity

$$P = \Delta SD/F \qquad 3.$$

If there were no force exerted on the product being rolled, the gauge would not be reduced and the delivery gauge from the roll stand would be equal to the entry gauge. If the roll force is caused to increase, the product is plastically deformed and the delivery gauge decreases. The inverse slope of the mill characteristic curve **200** is the mill spring modulus K having the units of inches per 10^6 lbs., and the inverse slope of the product characteristic **202** is the product plasticity P having the units of inches per million pounds.

The workpiece delivery gauge is determined by the equilibrium point **204** where the roll force exerted by the roll stand is equal to the force required to deform the product. Changes in workpiece entry gauge and/or changes in workpiece product hardness result in a change in roll force and the workpiece delivery gauge. The gauge control must move the screwdown to adjust the roll opening of the roll stand to correct for these changes in workpiece delivery gauge.

One advantage of using a roll force gauge control system is the ability to detect changes in workpiece delivery gauge the instant those changes occur as the product is passing through the mill stand. A shift in workpiece delivery gauge or thickness can be caused by a change in workpiece entry gauge, or a change in workpiece hardness (usually caused by change in workpiece temperature); this change in delivery gauge can be immediately detected by monitoring the roll separating force of the roll stand.

As the head end of the workpiece strip enters a given stand (N) of the rolling mill, the initial or lock on screwdown position $SDLO(N)$ and lock on roll separating force $FLO(N)$ are measured to establish what workpiece delivery gauge should be maintain out of that stand (N). As the rolling proceeds, the instantaneous roll separating force $F(N)$ and screwdown $SD(N)$ are periodically monitored and any change in roll separating force $F(N) - FLO(N)$ is detected and compensated for by a corresponding change in screwdown position $SD(N) - SDLO(N)$. As shown in equation 4, the lock-on delivery gauge $GLO(N)$ for stand N is equal to the lock-on screwdown $SDLO(N)$ plus the lock-on force $FLO(N)$ multiplied by the known mill spring modulus $K(N)$. Equation 5 shows the delivery gauge $G(N)$ at any time during the rolling is equal to the screwdown position $SD(N)$ plus the roll separating force $F(N)$ multiplied by the mill spring modulus $K(N)$. The gauge error $GE(N)$ shown in equation 6 is derived by substracting the lock-on gauge equation 4 from the gauge equation 5.

$$GLO(N) = SDLO(N) + K(N) * FLO(N) \qquad 4$$

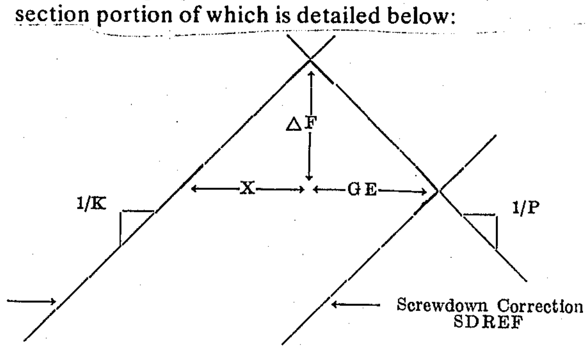
$$G(N) = SD(N) + K(N) * F(N) \qquad 5$$

$$G(N) - GLO(N) = \text{GAUGE ERROR} = SD(N) - SDLO(N) + [F(N) - FLO(N)] * K(N) \qquad 6$$

FIG. 3 illustrates the operation of a roll force gauge error detection system, with the dotted mill spring curve **201** and the dotted product plasticity curve **203** representing the head-end operation lock-on conditions and the respective solid line curves **200** and **202** representing the present or instantaneous operation condition. As compared to the original lock-on conditions, the stand screwdown controlled roll opening $SD(N)$ as shown in FIG. 3 has moved in the opening direction and the roll separating force $F(N)$ has increased compared to the lock-on force $FLO(N)$, probably because of a hard and cold portion of the workpiece strip now passing through the roll stand N.

The correction in screwdown position is not only dependent upon the gauge error, but also on the mill spring modulus $K(N)$ and product plasticity P values. FIG. 4 illustrates a system operation with the gauge error $GE(N)$ removed by a stand screwdown correction $SDREF(N)$; the screwdown correction is shown to be approximately twice the size of the gauge error. This operation will actually result in an increase in roll force because of the greater workpiece gauge reduction taken. Very soft workpiece products require a screwdown correction very nearly the same as the delivery gauge error, but very hard workpiece products require a larger screwdown correction compared to the delivery gauge error.

The desired screwdown movement SDREF(N) for stand N to correct a gauge error $GE(N)$ is illustrated by the following equations in relation to FIG. 4; the intersection portion of which is detailed below:



$$\text{Screwdown Correction SDREF(N)} = X + GE(N) \quad (7)$$

$$X = K(N) * F(N) \quad (8)$$

where ΔF(N) is the change in roll force when this gauge error is corrected.

$$F(N) = \frac{GE(N)}{P} \quad (9)$$

$$X = K(N) * \frac{GE(N)}{P} \quad (10)$$

where this equation is obtained by substituting Equation 9 into 8

$$\text{Screwdown Correction SDREF(N)} = K(N) * \frac{GE(N)}{P} + GE(N) \quad (11)$$

$$SDREF(N) = GE(N)\left[\frac{K(N)}{P(N)} + 1\right] \quad (12)$$

where Equation 10 is substituted in Equation 7.

The workpiece slab is usually supported prior to the slab passing through the rolling mill, in the heating zone of a furnace by water cooled skids. If the heat energy distribution soak zone of the furnace does not do an adequate job, cold skid marks will result at spaced locations along the length of the slab. These cold skid marks require rapid gauge error correction during the workpiece passage through a rolling mill, but, one of the problems in any gauge control system is the limited speed of the individual stand screwdown system and the inability of the stand roll opening to follow rapidly changing gauge error causing disturbances as they pass through the rolling mill.

FIG. **5** shows the response of the gauge control system on the first stand of a rolling mill as a skid mark is passing through the mill stand. The top curve shows the per unit roll separating force plotted against time. The gauge error is detected immediately, but the first stand screwdown system is unable to make any appreciable movement for almost one-half a second. The screwdown system is unable to bring the workpiece delivery gauge back to the desired value until after more than half the skid mark has passed through the mill stand and the screwdown of that stand is running at maximum speed in the down direction. Before the stand screwdown system can be reversed and brought back to its desired on gauge position, a considerable amount of light gauge workpiece product is rolled.

FIG. **6** shows the conditions in the second roll stand of the rolling mill when this same skidmark containing workpiece portion arrives about 1.5 seconds later. Even more light gauge strip is rolled because of the over correction of the relatively slow screwdown system of the second stand.

This condition of over correcting for rapidly changing gauge errors is improved by limiting the incremental corrections which can be made on a given stand. Limiting the incremental error limits the speed of the screwdown change of that stand because of the screwdown position regulator slowdown characteristic. The results of such limited corrections are shown in FIGS. **7** and **8**. It should be noticed that the positive gauge error is slightly higher because of the limited correction speed, but the overcorrection in the light direction is greatly improved on both the first roll stand and the second roll stand.

The illustrations show how the roll force rises and falls, and how the screw position correction takes place to try to remove that error, and the resulting gauge error that goes heavy before an adequate screw movement can be effected. The screws are then moving either down or up in a direction, as desired for proper error correction at a high rate when the gauge error is removed and in fact overshoot some before they can be stopped. This is a good illustration of why the feed forward concept is required, since the screws of a given stand cannot follow the disturbances; if the screws are permitted to try to correct for the gauge error disturbances present in the work strip, they will overcorrect by getting up to a high speed of corrective operation and then cannot be stopped in time to avoid some overshoot in error correction position.

In order to improve the delivery gauge control performance for a rapidly changing gauge error, it is possible to detect that error in a given workstrip portion at a given roll stand ($N$and cause a screwdown correction to be made in the following roll stand (N+1) in anticipation of the arrival of that workstrip portion containing the detected gauge error. FIG. **9** shows one example of the results of this type of error anticipation gauge control. The particular gauge error detection system for stand (N) looks at the gauge error leaving stand (N). Assume that stand (N) is spaced from stand (N+1) by a distance of 18 feet, and the workpiece is moving from stand (N) to stand (N+1) at a speed of 600 feet per minute. The screwdown mechanism of stand N takes action at 0.2 seconds because of a continuing rising high gauge condition as shown in FIG. 7. Since the transport time delay from stand (N) to stand (N+1) is 1.6 seconds, this gauge error containing portion of strip is expected to arrive at stand (N+1) at 1.8 seconds and stand (N+1) applies a DOWN correction for 0.8 of a second in the downward direction. This means that the screwdown system of stand (N+1) goes DOWN, starting at 1 second and continuing to 1.8 seconds, in anticipation of the heavy gauge error from stand (N) arriving at that stand (N+1). Similarly, a light gauge rising error was detected in stand (N) at 1.5 seconds causing an UP correction at stand (N+1) from 2.3 seconds until 3.1 seconds. This causes some slight under gauge prior to the arrival of the gauge error at stand (N+1) and some overshoot after the gauge error leaves stand (N+1), but the peaks of the gauge errors are reduced.

FIG. **10** illustrates the well known roll stand screwdown controlled roll opening adjustment characteristics which permit a determination of response time required to make a desired roll opening adjustment of a given roll stand. Four typical distance vs. speed curves for different acceleration rates show the time required (dotted lines) and the speed reached for various screwdown moves starting at zero speed.

Since the fast changing errors are too fast for the screwdown system in the error detecting stand, the screwdown system on the following stand can be moved in anticipation of the error arriving at the following stand. In order to minimize the off gauge material during the anticipatory movement, the following stand screwdown positioning system is given a large correction to achieve maximum speed of correction.

The automatic gauge control program of the present invention, as illustrated by the program flow chart shown in FIG. **11** is indexed from the first stand through the last stand and is run through every 0.2 second, as determined by a well known synchronizer interrupt subroutine within the digital computer system **12** of FIG. **1**.

The gauge error GE for stand N and desired screwdown correction DELS for stand N to remove that gauge error are determined at program step 1 by measuring the change in roll force from the lock-on value $FL0(N)$ to the present value $F(N)$ and the change in screwdown position from the lock-on value $SDL0(N)$ to the present value $SD(N)$, and converting through a predetermined relationship of these values into a gauge error GE, using the known mill spring modulus $K(N)$ for stand N. The gauge error GE is converted into a stand (N) screwdown correction $DELS(N)$, by multiplying the gauge error GE by a gain factor $K(N)/P(N) + 1$, which is a predetermined function of the mill spring modulus $K(N)$ and the workpiece plasticity $P(N)$ for the roll stand N, as set forth in above equation (12). Both $K(N)$ and $P(N)$ are in units of inches per 10^6 lbs. for this purpose. This screwdown correction $DELS$ is stored in a temporary location TEMP for use during the next part of this same gauge control program, where comparisons are made with previously established values for the stand N screwdown correction, during the last previous run or scan through this same gauge control program. Program steps 2 and 6 determine if the incremental screwdown correction $DELS$ is greater than predetermined limit values, for example, ±0.005 inch.

For the purpose of illustration, assume that the detected gauge error GE is falling and there is a need to increase the roll opening of stand N, if the screwdown correction DELS exceeds the positive limit value of +0.005 inch, the program advances to step 3 where the screwdown correction DELS is limited to an even smaller value, such as +0.002 inch, as the partial gauge error correction to be made by stand N. At program step 4 a comparison is made between the present screwdown correction which is stored in TEMP and the previous run through the program determined screwdown correction $PDELS(N)$ for this same stand N, which value of the latter previous screwdown correction $PDELS(N)$ was remembered at program step 16 during the last previous run through the control program, as will be explained in greater detail in relation to that program step **16**.

If the comparison at program step 4 finds that the present and positive screwdown correction is continuing to rise in magnitude as compared to the last previous such correction, this comparison indicates that a correction should be anticipated for the next stand (N+1). The program then advances to step 5, where a check is made to see if an earlier correction is already in progress for stand (N+1), as indicated by the ON time for the UP screwdown correction ONU (N+1) being set equal to 1,000. If such an earlier correction is already in progress, the now established screwdown correction TEMP is not desired to be fed forward to control the roll opening of stand (N+1). But if no such earlier established correction is in progress, the program advances to step 13 where the necessary timing is set up for feeding a desired correction to the next stand (N+1) in anticipation of this sensed large, rising and positive screwdown correction which is anticipated in the next stand (N+1).

The effective screwdown corrections which are fed to the next stand (N+1) are controlled by application internal timing values.

The predetermined application interval timing values, for purpose of example, can typically be the following in terms of seconds duration of the applied anticipate gauge error screwdown correction.

Stand Number (N+1)	2	3	4	5	6
DOWN ACTD(N+1)	0.8	0.8	1.0	1.0	1.0
UP ACTU(N+1)	0.8	0.8	0.8	0.8	1.0

For a typical tandem stand rolling mill, the screwdown electric drive apparatus is duplicated for all stands and each such drive apparatus can have an acceleration rate of 0.030 in/sec^2. In FIG. **10** there is shown a plot of the maximum speed of a screwdown apparatus versus inches of adjustment to illustrate how much adjustment in inches of roll opening correction can be realized in terms of the time interval that a roll opening correction signal is applied.

A clock counter is continually running in the digital computer system **12** shown in FIG. **1** to measure process control time, and certain ON and OFF timing values are chosen in relation to this count, for determining the time at which the screwdown corrections in either the UP or the DOWN direction are turned ON or are turned OFF. The stand roll opening adjustment is turned OFF when the work strip portion containing the gauge error just detected has arrived at the next stand (N+1); roll opening adjustment correction then is no longer required, since the next stand (N+1) can now sense the hardness or softness of the workpiece strip and take care of the desired gauge error correction by its own roll force gauge error detecting system. The desired screwdown correction *DELS*(N) is turned ON a predetermined time before the workpiece portion containing the detected gauge error is expected to arrive at the next stand (N+1); these screwdown correction time interval values are defined as ACTD(N+1 for the DOWN direction, as shown at program step 10 and as ACTU(N+1) for the UP direction, as shown at program step **13**. The latter time values ACTD(N+1) and ACTU(N+1) are predetermined time values, as illustrated above for the respective stands, for the anticipated screwdown corrections, and are typically from 0.5 to 1.5 seconds in magnitude.

At program step 13 where the feed forward error screwdown correction is to be timed for the UP direction, the first operation is to calculate the transport time delay TTD, which is equal to the known stand spacing, between roll stand N and the next succeeding roll stand (N+1), divided by the sensed operating speed FPM(N) of the roll stand (N), in feet per minute, multiplied by a conversion constant to convert the transport time delay into the units used in the operation of the clock counter, i.e., tenths of a second. The time OFFU(N+1 at which the UP screwdown correction shall be turned off at the next stand (N+1) is set equal to the present counter level COUNT plus this established time delay TTD. The time ONU(N+1) when this UP correction should be turned ON is the off time OFFU(N+1) minus the duration ACTU(N+1) that this screwdown correction is to be applied to adjust the roll opening of the next stand (N+1).

Such a control system of feeding forward UP and DOWN screwdown corrections is likely to have instances where these corrections will overlap. An example to illustrate such an overlap is generally shown in FIG. **12**. In FIG. 12A there is shown an UP correction already determined for the next stand (N+1), with the ON signal for this UP correction being at a count lever of **10** and the OFF signal being at a count lever of **20**, and a DOWN correction determined for stand N+1 starting at count level **18** and ending at count level **28**. This timing pattern would cause these UP and DOWN corrections to overlap.

To correct for this condition, the control program shown in FIG. **11** at step 14 and step 15 detects this overlap and modifies the OFF values for both the DOWN and the UP corrections to shorten both the respective amounts of correction provided as required to prevent the overlap. In FIG. **12** there is shown how the control program would modify the OFF signal of the DOWN correction to a count level of **17** and modify the OFF signal of the UP correction to a count level of **26**, with a unity count being provided between the OFF timing of the DOWN correction and the ON timing of the UP correction in accordance with program step 15 where OFFD(N+1) is made equal to ONU(N+1 minus one.

Relative to the feed forward of a negative (DOWN) correction, a generally similar set of logic is provided for the screwdown corrections in the DOWN direction, where at program step 7 through step 9 the large, increasing negative corrections are detected, and at steps 10 through 12 the DOWN correction timing is similarly established for the roll opening adjustment of the next stand (N+1).

At program step 16 the required correction TEMP for the present stand (N) is remembered in location PDELS(N), so that it can be used during the next gauge control action determining run through the control program for this same stand (N).

Program steps 17 through 27 are used to detect feed forward corrections from the previous stand (N−1). Comparisons are made for the OFF and ON signals for a DOWN correction as compared to the present count level on the clock counter, at program steps 17 and 19. And if the count is after the ON time and before the OFF time, the program advances to step 21, where the screwdown correction DELS(N) for this stand (N) is decreased by an arbitrary value, for example, 0.020 inch, in anticipation of a gauge error coming from the prior stand (N−1). If the count is larger than the OFF time for the DOWN correction, the program advances to step 18, where the ON time is set to an arbitrarily high number, for example, 1,000, to indicate a correction ended and is no longer in progress, this setting will be used at program step 9 during the next run through the control program to detect if a DOWN correction is in progress. Similar checks are made at program steps 20 and 23 to determine whether an UP correction is required, and if the screwdown correction for the stand (N) is increased by an arbitrary amount at program step 24, for example by 0.020 inch, or is unchanged if a correction is not called for.

The screwdown reference SDREF(N) for the stand (N) has been determined at program step 25, where the present screwdown feedback is changed by the screwdown correction DELS(N), which includes the limited correction for errors in stand (N) plus any additional corrections fed forward from the previous stand (N−1) as detected at program steps 21 or 24.

At program step 26 a determination is made of stand N is the last stand of the rolling mill. If stand N is the last stand, the control program operation ends for this run through the program. If stand N is not the last stand, the program indexes to the next stand for a similar determination of the desired gauge control operation as previously described.

The digital computer system 12 shown in FIG. **1** is operative with the control program shown in FIG. **11**, such that whenever a determination is made of the value of some quantity, like the gauge error *GE* or the screwdown correction DELS and so forth, to the left of each equal sign, it is stored at the appropriate address location in the memory of the digital computer operative in that digital computer system.

In FIG. **13** the curve **300** illustrates a typical skid mark caused workpiece gauge error at stand *N* of the rolling mill. The curve **302** illustrates the pattern of the successive screwdown corrections *DELS*(*N*) which would be established by the gauge control program shown in FIG. **11**. The point **304** on the curve **302** could be a determined screwdown movement correction, as stored at temporary location TEMP. The point **306** on the curve **302** could be a previous run through the control program determined screwdown correction PDELS(*N*) that was remembered at program step 16 during the last previous run through the program. It is noted that the value of TEMP is shown as 0.008 inch and the value of PDELS(*N*) is shown as 0.006 inch, so the comparison at program step 8 would indicate a rising negative correction such that the program would now advance to program step 9 to determine if a DOWN correction is in progress from a previous run through the control program.

The functional block diagram of FIG. **14** illustrates the general operational concept of the present invention. In regard to the detected workpiece delivery gauge error at stand *N*, there is determined the screwdown correction that is needed to correct this gauge error. Then comparisons are made between this now determined screwdown correction and the previously determined screwdown correction to detect if there are any large increasing respective positive or negative going screwdown corrections taking place. If there are such screwdown corrections taking place, it is desired to control the ON time to begin the correction and the OFF time to stop the correction, so a determination of this timing in relation to the present moment could level in a clock counter and predetermined time durations for such an anticipated screwdown correction to be fed forward to the next succeeding roll stand (*N*+1). The screwdown correction determined by this run through the control program is now remembered for the purpose of this same comparison during the next succeeding run or control scan through the control program. Then a determination is made to see what screwdown correction was fed forward from previous stand (*N*−1) during this same run through the control program. And the determined stand (*N*) screwdown correction is applied to control the roll opening or screwdown position of stand *N*. The teachings of the present invention could readily be practiced by use of an analog control system embodiment by persons skilled in the rolling mill control art, and in accordance with the disclosure of FIG. **14**. However, it is believed that the best mode for the practice of the present invention would be through use of the digital computer system control program, as illustrated by the logic flow chart shown in FIG. **11**, particularly when it is desired to use a programmed digital computer system 12 to provide schedule calculations and data logging for the rolling mill operation.

I claim:

1. A gauge control system for a rolling mill having at least one rolling stand, with said one rolling stand having a controlled roll opening through which a moving workpiece is transported, said system comprising

means for determining a gauge error in a portion of said workpiece at a predetermined distance prior to said one rolling stand,

means for determining a correction of the roll opening of said one rolling stand in relation to said gauge error to control the workpiece delivery gauge from said one rolling stand,

means for controlling the roll opening of said rolling stand in accordance with said correction,

means for determining the length of time said correction is applied to control said roll opening,

with said means for controlling the roll opening of said rolling stand being operative to terminate said correction when said workpiece portion arrives at said rolling stand and being operative to control said roll opening for a time interval substantially equal to said length of time.

2. A gauge control system as set forth in claim **1**, including a digital computer system,

said computer system having an output coupled to said means for controlling the roll opening of said rolling stand, and

said length of time determining means including a stored control program operative with said digital computer system to determine said length of time.

3. A gauge control system as set forth in claim **2**, wherein said computer system includes a stored control program operative to determine said gauge error.

4. A gauge control system as set forth in claim **1** wherein said gauge error determining means is operative substantially throughout the rolling period of said workpiece.

5. A gauge control system for a rolling mill having at least two rolling stands, with the second of said stands having a controlled roll opening through which a moving workpiece is transported, said system comprising

means for determining a gauge error at a first of said rolling stands,

means for determining a correction of the roll opening of said second of said rolling stands to control the workpiece delivery gauge from said second rolling stand,

means for controlling the second rolling stand roll opening to apply said correction,

with said correction determining means including means for establishing an ON time and an OFF time for applying said correction to the roll opening of said second rolling stand, in accordance with the movement of said workpiece between said first and second rolling stand, such that the application of said correction is terminated when said determined gauge error arrives at the second rolling stand.

6. A gauge control system as set forth in claim **5** wherein said means for determining the ON time and the OFF time of said correction includes a programmed digital computer system,

said computer system having a program for determining the OFF time in accordance with the transport time delay of said workpiece movement between the first and second rolling stands and for determining the ON time as a predetermined time period before said OFF time.

7. A gauge control system as set forth in claim **6**, wherein said means for determining the ON time and

the OFF time is operative to determine said OFF time and then determine said ON time in relation to said OFF time.

8. A gauge control system for a rolling mill as set forth in claim 5, said system including

means for detecting the roll force of said first rolling stand,

means for detecting the roll opening of said first rolling stand,

with said means for determining a gauge error being operative in relation to said detected roll force and said detected roll opening and a predetermined roll force and a predetermined roll opening for said first rolling stand.

9. A gauge control system as set forth in claim 5 with said means for establishing an ON time and an OFF time being responsive to the spacing between said first rolling stand and the second rolling stand and being responsive to the operating speed of the first rolling stand.

10. A gauge control system for a rolling mill having at least two rolling stands, with each of said stands having a controlled roll opening through which a workpiece is passed, said system comprising

means for determining a screwdown correction relative to a workpiece delivery gauge error in a portion of said workpiece passing through a first of said rolling stands,

means for determining a correction of the roll opening of a second of said rolling stands in response to said screwdown correction to provide a desired workpiece delivery gauge from said second rolling stand,

means for determining the time interval required for said workpiece portion to be transported for a predetermined distance,

and means for controlling the correction of the second rolling stand roll opening having an ON time for said correction and an OFF time for said correction in accordance with said time interval and such that said OFF time is scheduled in relation to the arrival of said workpiece portion at said second rolling stand.

11. A gauge control system as set forth in claim 10 wherein said means for determining the screwdown correction and said time interval includes a programmed digital computer system,

said computer system being coupled to said means for controlling said correction of the second rolling stand roll opening.

12. A gauge control system as set forth in claim 10, wherein said screwdown correction determining means operates in response to the presence of said workpiece in the roll opening of at least one of said first and second rolling stands.

13. A gauge control system as set forth in claim 10, including

means for detecting the roll force of said first of said rolling stands,

means for detecting the roll opening of said first rolling stand,

with said means for determining said screwdown correction being operative in relation to said detected roll force and said detected roll opening and a predetermined roll force and a predetermined roll opening for said first rolling stand.

14. A gauge control system as set forth in claim 13 wherein the rolling mill is a tandem mill having a plurality of roll force gauge controlled stands, with each of the latter stands being provided with means for detecting the stand roll force and the stand roll opening,

with said screwdown correction determining means being operative to determine a screwdown correction for respective selected stands of said rolling mill,

and with said correction controlling means being to correct the roll opening of a succeeding stand in relation to each such screwdown correction that is determined.

15. A gauge control system as set forth in claim 10, including

means for detecting the roll force F_N of said first of said rolling stands.

means for detecting the roll opening SD_N of said first rolling stand,

with said means for determining said screwdown correction $SDREF_N$ being operative in relation to said detected roll force F_N and said detected roll opening SD_N and a predetermined roll force FLO_N and a predetermined roll opening $SDLO_N$ for said first rolling stand in accordance with the relationship

$$SDREF_N = SD_N + \left[\frac{K_N}{P_N}+1\right][(F_N - FLO_N)K_N + SD_N - SDLO_N]$$

where K_N is a predetermined mill spring characteristic and P_N is a predetermined workpiece plasticity characteristic.

16. A gauge control system as set forth in claim 10, including

means for determining said OFF time in relation to said workpiece portion passing through said second rolling stand and for determining said ON time in relation to said OFF time and said time interval.

17. A method of controlling workpiece gauge for a rolling mill as set forth in claim 10, wherein the length of time determining step includes the operation of a programmed digital computer system to sense the movement of the workpiece portion for said predetermined distance and to determine said length of time in relation to the travel time delay required for the workpiece portion to travel said distance.

18. A method of controlling workpiece gauge for a rolling mill having at least one rolling stand, with said one rolling stand having a controlled roll opening through which a moving workpiece is passed, the steps of said method comprising

determining a gauge error in a portion of said workpiece at a predetermined distance ahead of said one rolling stand in accordance with the movement direction of said workpiece through said one rolling stand,

determining a correction to control the roll opening of at least said one rolling stand to provide for correct delivery gauge from at least said one rolling stand,

determining the length of time said correction is applied to control the roll opening of at least said one rolling stand in relation to the movement of the workpiece portion for said predetermined distance, and controlling the roll opening of at least said one rolling stand for said length of time in accordance with said correction and such that the application of said correction is completed in relation to the arrival of said workpiece portion at said one rolling stand.

19. A method for providing gauge control in a rolling mill as set forth in claim 18 wherein said correction determining step includes the operation of a programmed digital computer system to determine said correction in the roll opening of said one rolling stand in accordance with the relationship

$$DELS = GE\left[\frac{K_N}{P_N}+1\right]$$

where *DELS* is the determined correction, *GE* is the determined gauge error, K_N is predetermined mill spring characteristic for said one rolling stand, and P_N is the predetermined plasticity characteristic of said workpiece.

20. A method of controlling the workpiece gauge for a rolling mill having at least two rolling stands with respective screwdown controlled roll openings through which a workpiece is passed, the steps of said method comprising

detecting the roll force of one of the rolling stands,

detecting the screwdown position of said one rolling stand,

determining the workpiece gauge error for said one rolling stand in accordance with detected roll force and detected screwdown position values and predetermined roll force and predetermined screwdown position values,

determining a correction to be made in the screwdown position of another of the rolling stands to provide for correct delivery gauge from said another rolling stand,

determining the time interval required for the workpiece portion for which gauge force error is determined to pass from said one rolling stand to said another rolling stand,

with said correction determining step including predictively determining said correction in the screwdown position of said another rolling stand in relation to the magnitude of said gauge error,

and controlling the screwdown position of said another rolling stand in a predetermined relationship to said time interval for effecting said correction before said workpiece portion arrives at said another rolling stand.

21. A method of controlling the workpiece gauge for a rolling mill as set forth in claim 20 wherein the gauge error determining step includes the operation of a programmed digital computer system to sense the detected roll force and detected screwdown position values and to establish the predetermined roll force and predetermined screwdown values and to calculate the gauge error for said one rolling stand.

22. A method of controlling the workpiece gauge for a rolling mill as set forth in claim 21 wherein said correction determining step includes the operation of said programmed digital computer system to determine said correction in the screwdown position of said another rolling stand.

23. A method for providing gauge control in a rolling mill having at least one rolling stand with a controlled roll opening through which a workpiece is transported, the steps of said method comprising

detecting a representation of gauge error in a workpiece portion located at least a predetermined distance ahead of one rolling stand of said rolling mill,

determining the time interval required for said workpiece portion to be transported said predetermined distance,

providing a gauge error correction in accordance with the magnitude of said detected gauge error representation,

and controlling the roll opening of said one rolling stand in accordance with said gauge error correction for a time period determined by said time interval and such that said roll opening control is completed before said workpiece portion is transported to said one rolling stand.

24. A method of controlling gauge in a rolling mill having at least two rolling stands with respective controlled roll openings through which a workpiece is passed, the steps of said method comprising

detecting the roll force F_N of a first of the rolling stands,

detecting the roll opening SD_N of said first rolling stand,

determining the gauge error *GE* for said first rolling stand in accordance with detected roll force F_N and detected roll opening SD_N values and predetermined roll force FLO_N and predetermined roll opening $SDLO_N$ values,

determining a correction *DELS* to be made in the roll opening of at least a second rolling stand to provide for corrected delivery gauge from at least said second rolling stand in accordance with a predetermined relationship

$$DELS = GE\left[\frac{K_N}{P_N}+1\right]$$

where K_N and P_N are predetermined rolling stand operational characteristics

and controlling the roll opening of said second rolling stand to effect said correction for a time interval related to the workpiece transport time between said second rolling stand and the rolling stand prior to said second rolling stand and such that said roll opening control is completed before said workpiece gauge error arrives at said second rolling stand.

25. A method for providing gauge control in a rolling mill as set forth in claim 24 wherein the gauge error determining step includes the operation of a programmed digital computer system to sense the detected roll force F_N and detected roll opening SD_N values and to establish the predetermined roll force FLO_N and predetermined roll opening $SDLO_N$ values and to calculate the gauge error GE for said first rolling stand.

26. A method for providing gauge control in a rolling mill as set forth in claim 25 wherein said correction determining step includes the operation of said programmed digital computer system to predictively deter-

mine said correction DELS in the roll opening of said second rolling stand.

* * * * *