POSITION MONITORING DEVICES (U)

L. G. Whitten

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UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** *under* **U. S. GOVERNMENT** **Contract W-7405 eng 26**

**UNION
CARBIDE**

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Y-12 PLANT

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With the US Atomic Energy Commission

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ABSTRACT

This presentation is limited to those devices which monitor position over ranges of a few inches to several feet. Mechanical, optical, and electrical concepts are covered. Clearly defined advantages and disadvantages are pointed out; however, no attempt is made to evaluate any one system with respect to another.

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INTRODUCTION

Many systems are currently available for the monitoring of position. A resume of these systems is presented in this report with emphasis on those systems which have a range from a few inches to several feet. An attempt has been made to group the systems by operation: mechanical, optical, or electrical. However, it must be realized that the more complex systems will encompass two or more classes of operation.

In each case, where possible, a system is first explained according to the basic concept. Next, an example is given of a practical application. If applicable, the accuracy of the system is also included.

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SUMMARY

Many monitoring systems have been studied at the Y-12 Plant both as to their basic concept and their possible application to Plant requirements. Obviously each system has certain advantages and disadvantages, depending on the proposed application. This presentation does not attempt to evaluate any one system with respect to the others, only to indicate its accuracy and applicability where possible.

Particular emphasis has been devoted to the newer systems such as the hydrostatic nut, the lined-scale interpolator, and the direct-reading laser interferometer.

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POSITION MONITORING DEVICES

MECHANICAL SYSTEMS

Screw and Nut

The screw and nut forms a basic part of one of the oldest known position-monitoring devices. Astronomers used this principle of amplification by a screw-in device over three hundred years ago. The amplification which can be obtained is based on the ratio of circumferential to lateral movement. Amplification in the order of 200 - 400X is most commonly found. Higher amplifications require larger reading drums and/or finer pitch screws; lower amplification does not produce the desired precision. A typical high-precision screw and nut schematic is presented in Figure 1. The nut is depicted as being a large bronze piece which covers several threads. The soft metal minimizes wear on the screw and helps to distribute single-pitch lead errors uniformly. A typical machine arrangement is shown in Figure 2. Large ten-pitch screws are used to position and to monitor the position of both the longitudinal and transverse slides on this machine. The accuracy, with unidirectional positioning, is 35 microinches. Because of the clearance between the nut and the screw it is impractical to accurately lap both sides of the screw. Therefore, only one side is finished and all final settings must be made approaching from the same direction.

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Figure 1. BRONZE NUT AND SCREW.

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Figure 2. COORDINATE MEASURING MACHINE.

Ball-Nut Screw

The ball-nut screw, which is shown schematically in Figure 3, overcomes some of the disadvantages of the standard nut and screw. Recirculating balls are carried in the groove formed between the screw and the nut. Sliding friction is virtually eliminated with the substitution of rolling friction. Very high preloads can be applied to reduce the backlash without appreciably increasing the rotational force.

A typical installation that utilizes the ball-nut screw is shown in Figure 4. It is significant to note that a majority of today's tape-controlled machine tools and gages feature the ball-nut screw for position and control. Sizes range from 5/16 inch to 6 inches in diameter with lengths made to order. Because of the insertion of the balls between the nut and the screw, the thread pitch is usually limited to the range of one to ten threads per inch. At the present time, one of the major disadvantages of this device is that the pitch diameter of the screw is seldom found to be concentric with the cylindrical locating surfaces at the ends of the screw. This disadvantage causes either translation of the nut in a plane perpendicular to its direction of travel, bending of the screw as it rotates, or both.

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Figure 3. BALL-NUT SCREW.

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Figure 4. TAPE-CONTROLLED THREE-AXIS MILLING MACHINE.

Hydrostatic Nut

The hydrostatic nut, in theory, overcomes the disadvantages of both the standard and the ball-nut screws. As shown schematically in Figure 5, the nut is completely isolated from the screw by either a gas or liquid film. This separation eliminates wear on both members and reduces the frictional component to that of fluid friction. At the present time, work on the hydrostatic nut within the United States is limited to laboratory development. An "anti-backlash" nut is available which uses hydrostatic pressure to force two nut sections apart and

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Figure 5. HYDROSTATIC NUT.

maintain pressure on both flanks of the screw thread. However, since a hydrostatic film is not maintained between the nut and the screw, it is not considered a true hydrostatic nut.

In England, true hydrostatic nuts are being produced. The basic thread form is an Acme thread with extended root and tip clearance to provide a double depth. Because of the complicated oil supply and return system within the nut and nut threads, the pitches are relatively coarse, such as four threads per inch on a "fine" nut and one thread per inch on a "coarse" nut. System stiffness in excess of 10 million pounds/inch is not uncommon.

Rack and Pinion

This system, shown schematically in Figure 6, consists of a rack and pinion operating through anti-backlash gearing. With proper gear selection, conversion is made from the angular pinion shaft position into decimal position information. This device is strictly for position indication and is not associated with the drive mechanism. Therefore, it can be retrofitted to most machine tools. Figure 7 shows such a system installed on a LeBlond lathe and Figure 8 shows the system retrofitted to a Cincinnati mill. As would be expected, the accuracy of the rack and

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Figure 6. RACK AND PINION READOUT SYSTEM.

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Figure 7. RACK AND PINION SYSTEM AND LATHE.

pinion system is less than that of other mechanical systems. However, accuracies in the range of 1.0 to 0.5 mil can be readily obtained.

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Figure 8. RACK AND PINION SYSTEM ON A MILL.

End Standards

The end standard or "lug bar" system is one in which known lengths are indexed in place to provide the desired length. Each indexing set consists of dials which manipulate a series of end standards manufactured to Class A gage-block accuracy. A normal set consists of six dials which are connected to the six respective indexing drums; ie, one drum and dial for 10-inch increments, one for 1-inch increments, one for 0.1-inch increments, one for 0.01-inch increments, one for 0.001-inch increments, and one for 0.0001-inch increments. Figure 9 shows a typical lug-bar box and Figure 10 the lug-bar controls.

The primary disadvantages of such a system are: (1) the lug-bar errors are additive, and (2) dirt or other contaminants between the bars are detrimental to the readings and cause wear. However, because of the high contact pressures, the problem of contamination does not appear to be significant with proper use of dust covers.

Figure 11 shows a jig boring machine that utilizes the lug-bar or end-standard-type measuring system for positioning.

OPTICAL SYSTEMS

Line Standards

Scribed scales or "line standards" form one of the earliest methods of measurement. Normally, the scribe lines are 25 or 50 mils apart and require some sort of optical

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Figure 9. LUG-BAR BOX.

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Figure 10. LUG-BAR CONTROLS.

means to subdivide the scale into smaller divisions. Figure 12 shows a typical scale and optical reader. In this case the optical reader is a low-powered microscope ($\sim 30X$) equipped with a micrometer eyepiece which allows direct subdivision of the 50 mil-spaced scribe lines to 50 microinches. Scales and readers are also available in metric subdivisions.

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Figure 11. JIG BORER CONTROLLED BY A LUG BAR.

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Figure 12. LINE STANDARDS.

Another type of optical scale device is shown in Figure 13. On this device, the scale scribe lines are 25 mils apart. The lines are viewed with a 20X optical system to give an effective spacing of 0.500 inch. A spiral having a 0.500-inch lead is superimposed on a glass plate carrying a circumferential scale. Subdivision is accomplished by rotating the glass plate until the spiral line is coincident

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Figure 13. LINE STANDARD ON A MEASURING MACHINE.

with the projected scale scribe-line image. The reading is then taken from the circumferential scale.

Applications of these devices are shown in Figures 14 and 15. In Figure 14, the machine's measuring system in all three coordinates consists of built-in optical scales having 50-mil spacings. Figure 15 shows a machine on which the two coordinates in the horizontal plane make use of built-in optical scales with 50-mil spacing, but the vertical coordinate has been retrofitted with a 25-mil spacing scale.

Optical scales are renowned for their nonwearing qualities because there is nothing in contact with the scribed scale surface. In spite of this advantage, there are many overshadowing disadvantages. One of the major disadvantages is that once a line is scribed, its position cannot be corrected without either physically removing all the lines and starting over or applying mathematical corrections for proper readings. Since the scale must be highly reflective and must maintain its brilliance over long periods of time, the materials of construction are significantly limited to those which are corrosion resistant or "stainless". For the more precise work, differences in the coefficients of expansion between the scale and either the machine or the part being measured become a problem.

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Figure 14. THREE-AXIS MEASURING MACHINE.

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Figure 15. LINE STANDARD ON A JIG BORER.

DIG Scales

DIG scales are another form of scribed scales. However, due to the unique resolver system which is used to digitize the scale reading, they are treated here as a separate subject. The basic system is identical for both inch and metric measurement. For simplicity, only the inch system is discussed. The basic scale is shown in Figure 16. Notice that the fine graduations are supplemented by three rows of additional graduations. These additional graduations provide coding for coarse position information; ie, the XX.XX information. With such an arrangement there is no need to accumulate large counts, and accuracy is unaffected by power losses or stray pulses. Figure 17 shows the schematic of the DIG coarse encoder. The three-decimal coded-pulse trains which are generated by the coarse-scale images falling on the photodetectors are used to indicate the coarse position.

Figure 16. "DIG" INTERPOLATING SCALE.

The DIG fine-encoder schematic is shown in Figure 18. This encoder system is an integral part of the coarse encoder. In operation, counting is started by light passing through a slit and lens to a detector. Pulses are generated by the clock disc and counted until the "stop-counting" signal is generated by the first scale graduation after the start pulse. This system of interpolation is completely independent of clock-disc speed.

Figure 19 is a photograph of a 19-inch-long scale and the associated reader. The scale is mounted on a massive support bar. Figure 20 shows this scale and reader together with the associated digital display mounted on a measuring machine for evaluation. The errors throughout this system were found to lie within a total bandwidth of 0.1 mil.

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Figure 17. "DIG" INTERPOLATING SCALE COARSE ENCODER.

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Figure 18. "DIG" INTERPOLATING SCALE FINE ENCODER.

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Figure 19. "DIG" INTERPOLATING SCALE AND READER.

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Figure 20. "DIG" INTERPOLATING SCALE ON A MEASURING MACHINE.

To date, the only major problem which has been experienced with this system has been an overheating of the electronic components in the dust-free cabinet. Correction for this problem consisted of simply drilling two-inch-diameter holes in the cabinet to allow for adequate heat dissipation.

Long-Range Interferometer

The development of a stable, single-frequency, continuous-wave laser has moved the interferometer from a short-range laboratory instrument to a long-range practical shop tool. Interferometric measuring systems have been limited to those employing either fringe-fraction or fringe-counting techniques. Of these, only the fringe-counting technique is applicable when using the laser as the light source. Figure 21 shows schematically how the optical components of a typical interferometer are arranged with respect to the laser and the detectors. With such an arrangement, an interference fringe is generated each time the movable reflector moves a distance equal to $\lambda/4$, or about every 6.2 microinches.

Concurrent with the laser development it was necessary to develop adequate electronic counters. When used in a vibration environment, a unidirectional counter adds counts even though the average distance between the moving mirror and the beamsplitter remains unchanged. Therefore, high-speed bidirectional counters are required. Figure 22 shows a typical arrangement of both the optical and electronic circuitry. In addition to the counters it is desirable to have a computer to convert

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Figure 21. LASER LIGHT SOURCE.

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Figure 22. LASER OPTICAL AND ELECTRONIC COMPONENTS.

the fringe count to a digital metric or inch display. As shown, the computer can take care of corrections for the temperature of the part as well as corrections for atmospheric conditions which affect the laser wavelength.

The laser interferometer can be used in either of two modes of operation. Figure 23 shows the laser interferometer as a calibration device. It is mounted on a tape-controlled lathe and is being used to provide a comparison between the programmed and actual machine slide movement.

Figure 24 shows the second mode of operation. In this case the interferometer is used to generate pulses as the machine slide moves. These pulses are compared to pulses being generated by a tape-controlled unit. Differences between these two sets of pulses form error signals which are then used to control the direction of slide travel. When applied to two axes, this becomes a continuous-path, interferometric-feedback, tape-controlled control system.

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Figure 23. LASER AS A CALIBRATING DEVICE ON AN AUTOMATIC LATHE.

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Figure 24. LASER ON A HYDROSTATIC MEASURING MACHINE.

The laser interferometer is a high-resolution, long-range measuring system. As with any system, care must be exercised in its application. One common misapplication is that of installing the system on a large machine and expecting microinch accuracy at the gage head or machine tool. The interferometer does not correct for geometry errors between the measured axis and the measuring axis. Another common misapplication is that of expecting the accuracy to be the same

for long distances as it is for short distances. The system is basically a fringe counting system. These counts are multiplied by the wavelength to give the distance moved. Consequently, errors due to wavelength uncertainty are proportional to the distance traveled. Fortunately, this error is only about one part in 10 million or 10 microinches in 100 inches under standard environmental conditions.

A third source of error is operation under an intermittent condition, whereby motion due to reflector directional movement and vibration momentarily exceed the maximum fringe-count rate. The loss of a few counts may not be detectable except by a rerun or a continuous calibration between fixed points.

Ferranti System

This system is basically one which uses parallel-spaced gratings. One grating is a stationary-transmission type and the other a moving-reflection type. These are at a slight angle to each other to produce Moire fringes. Figure 25 is a typical Ferranti system schematic. Fringe cycles and fringe fractions are monitored to indicate the distance moved.

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Figure 25. MOIRE FRINGE SYSTEM.

Figure 26 shows a typical Ferranti scale and reader. Normally, the reader is mounted to a fixed member and the scale is mounted on the moving member. However, this arrangement may be reversed with no harmful effects to the system.

An arrangement for measuring vertical position is shown in Figure 27. In this arrangement, the original boring head has been removed from the SIP 7A and has

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Figure 26. FERRANTI SCALE AND READER.

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Figure 27. FERRANTI SYSTEM ON A LARGE MEASURING MACHINE.

been replaced with a square vertical ram having a 36-inch travel. This travel is monitored with the Ferranti measuring system.

ELECTRICAL SYSTEMS

Electrolimit Head

The electrolimit system consists of an "E" coil which operates in conjunction with a magnetic lug bar. In normal operation the lug bar is attached to the moving machine member. The "E" coil is mounted with respect to the base of the machine in such a manner that it can be accurately positioned over a range of one inch. The positioning of the coil is usually done through the use of a micrometer screw. In this manner the lug bar locates the inch increments and the moving coil interpolates between the inch positions. A typical layout of this arrangement is shown in Figure 28.

This system has been used primarily on jig borers and inspection machines operating under both manual and tape-controlled modes. Figure 29 is a photograph of a large X-Y coordinate tape-controlled inspection machine which uses this system. This system has two distinct advantages: (1) there is no contact, and consequently no wear, between the "E" coil reluctance pickup and the magnetic lug bar; and (2) it is only necessary for the magnetic positions of the lug bar to

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Figure 28. "E" COIL SYSTEM.

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Figure 29. "E" COIL ON AN AUTOMATIC MEASURING MACHINE.

be accurately spaced. The physical position of the lug is of little consequence which means that a lug position can be corrected by filing or honing metal from one side of the lug. If too much is removed, it is only necessary to remove a little from the other side to properly locate the magnetic center.

Accupin

The Accupin system is another inductor-type system and consists of magnetic pins protruding from a stainless steel base and extending into inductor cores. A schematic of this general system is presented in Figure 30. The head windings are on cores composed of magnetic laminations separated by nonmagnetic spacers. The inductance of the head winding depends upon the position of the magnetic pins with respect to the magnetic lamination stacks. The windings are arranged in pairs and spaced so that the inductance in one is a maximum when the inductance in the other is a minimum. This arrangement is applicable to both linear and rotary position sensing. Figure 31 shows the schematic arrangement for linear measurements and Figure 32 the arrangement for rotary measurement. Four inductor cores are used to sense linear position whereas eight cores are used to sense rotary position.

Long-Range Transducer

Long-Range Transducer is the name which has been applied to this system of making measurements over a range as great as 120 inches. Its basic operation is that of a capacitance-ratio bridge, as shown in Figure 33. Accuracy depends upon the balanced capacitor and ratio transformer, with the difference between the capacitor

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Figure 30. ACCUPIN MAGNETIC TRANSDUCER.

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Figure 31. ACCUPIN MAGNETIC LINEAR TRANSDUCER.

voltage and the ratio transformer applied to a null meter. The moving bar is composed of many segments. All segments except the one centered in the coil are

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Figure 32. ACCUPIN MAGNETIC ROTARY TRANSDUCER.

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Figure 33. LONG-RANGE TRANSDUCER.

shorted when a reading is made. Figure 34 shows a 35-inch-range vertical transducer mounted for testing. A closeup of the reading head and the segmented bar is shown in Figure 35. This system will be mounted on a jig borer in place of the boring head. Measurements can then be made throughout the 36-inch vertical motion.

Sogenique System

The Sogenique system is another long-range transducer system operating on the principle of a capacitance-ratio bridge. The system is shown schematically in Figure 36. Several forms of this transducer are fabricated as standard items. Measuring ranges vary from 0 - 0.1 to 0 - 50 inches, depending upon the form selection. A typical Sogenique bar and reader is shown in Figure 37. The addition of an electronic console completes the system. The null point is indicated by a center zero meter. An amplifier is used to increase the sensitivity. The location of the null point is given in digital form either by association with the balance control knobs or by direct display on indicating devices such as lamps.

Nultrax

The Nultrax transducer is a helical differential transformer and consists of a helical bifilar winding on a long cylindrical rod. This winding is a two-start spiral of insulated wire. The reader consists of another winding of short length inside a sleeve. Translation of the sleeve plus rotation of the rod is used to find the null point. Figure 38 is a schematic of this system. Accuracy is in the range of one part in 400,000 or about 30 microinches per foot.

Figure 39 is a photograph of a machine which uses the Nultrax system for position sensing under tape control. One advantage of this transducer is that near the null point it operates as a differential transformer. The phase-sensitive output, after amplification, may be used to drive an AC servomotor. This system is not commercially available at this time.

Inductosyn

The Inductosyn system is based on inductive coupling between air-spaced conductors. It is available in both rotary and linear modes of operation. A linear scale and reader is shown in Figure 40. The scale length of ten inches is the maximum length supplied which, when used with the four-inch reader, give a measuring range of six inches. Greater lengths are measured by coupling additional scales end to end until the desired distance is obtained. Due to this particular inductive arrangement, the rotary Inductosyn is only susceptible to non-cyclic errors.

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Figure 34. LONG-RANGE TRANSDUCER TEST ARRAY.

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Figure 35. LONG-RANGE TRANSDUCER READER.

Figure 36. CAPACITANCE-RATIO SYSTEM.

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Figure 37. CAPACITANCE-RATIO BAR AND READER.

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Figure 38. NULTRAX TRANSDUCER.

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Figure 39. MAGNETIC SCREW MEASURING MACHINE.

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Figure 40. INDUCTIVE SYSTEM SCALE AND READER.

The Inductosyn system has been used on many types of equipment. Systems include both original and retrofitted installations. An inductive system installation on a hydrostatic measuring machine, which uses both rotary and linear Inductosyn scales on the respective axes, is shown in Figure 41.

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Figure 41. INDUCTIVE SYSTEM ON A HYDROSTATIC MACHINE.