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COMPUTERIZATION OF GAGING EQUIPMENT

T. W. Robinson

**UNION
CARBIDE**

OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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

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ABSTRACT

Some newer applications have been made of the small, general-purpose digital computer in the field of dimensional gaging. Equipment has been developed that permits a wide, practical, and versatile utilization of the computer.

CONTENTS

SUMMARY	5
INTRODUCTION	6
COMPUTERIZED GAGING EQUIPMENT	7
Data Handling Devices	7
Numerically Controlled, Computer-Enabled Machines	11
Computer-Controlled Measuring Machines	15
Radius-Theta Gaging	16
Cartesian Coordinate	18
Conclusions	23
ACKNOWLEDGEMENTS	25
APPENDIX A	26
Typical Specifications for a Linear Displacement Measuring System	26
APPENDIX B	37
Description of Computerized Equipment	37
APPENDIX C	50
Lists of Additional "M" and "G" Codes	50

SUMMARY

The purpose of this report is to review some of the newer applications of the small, general-purpose digital computer in the field of dimensional gaging. This subject will deal, primarily, with the equipment and software that has been developed over the past few years for inspecting "products of revolution".

The philosophies presented and equipment used as examples demonstrate the wide and practical application of the computer's capability and versatility. Items reviewed in this document will include:

1. Utilization of the computer for complete machine control and data handling.
2. Interfacing with existing hardwired NC units for control and data handling.
3. Interfacing with hardwired servo control systems.
4. Interfacing with specialized gages in order to obtain minor machine control with an ability to achieve massive data handling.

INTRODUCTION

As recently as five to ten years ago, dimensional measurements at the Oak Ridge Y-12 Plant^(a) were generally limited to hardwired, numerically controlled (NC) equipment and techniques generally referred to as "open setup" or bench work.

NC and other hardwired controlled equipment had made great strides in the previous five to ten years, but lacked in flexibility and required a high degree of mechanical accuracy.

The ever-increasing need for higher accuracies and efficiencies coupled with the availability of the small, general-purpose digital computer created an atmosphere wherein the marriage of the computer to the existing equipment was advantageous. Paralleling these events was a requirement for an increase in capacity unobtainable without the procurement of additional equipment, thereby presenting an opportunity for equipment designs that were computer orientated from the start.

Historically, most manufacturers of precision equipment had not ventured into the gaging field, much less into computerized gages. Through the continued efforts of the Atomic Energy Commission, Union Carbide Corporation, and commercial gage manufacturers, a concerted effort was initiated to improve dimensional measurement technology, capacity, and capability. These efforts involved not only those parties just mentioned, but also several new entrants into the gaging field.

The results of these efforts can best be demonstrated by discussing a few examples that point out the application of the digital computer in the field of dimensional inspection.

(a) Operated by Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

COMPUTERIZED GAGING EQUIPMENT

DATA HANDLING DEVICES

Marriage of the digital computer to dedicated gaging systems demonstrates its data-handling applications. The computer in this type of application usually has no control over the dedicated gage (gage designed specifically to measure a feature or features of one part type) other than to activate the rotary table and transducers during an inspection sequence. Its primary function is data handling for such operations as: (1) template error correction, (2) LVDT calibration, (3) part-offset correction, (4) part-tilt correction, (5) part vertical-shift correction, (6) collection of part data, (7) digital data output, and (8) storage of data for future processing in a multistage process.

However, due to the sophistication of these gaging systems, the computer is also used as a status control device to insure proper sequence of operations and protection of the operator, gaging equipment, and part.

Figures 1 through 3 provide views of some typical gaging systems. Use of the "status word" is all important. It enables the computer to determine whether the equipment is properly set up and ready to perform a particular operation. Upon receipt of a "start" signal, the computer scans existing functional conditions and stores the data in a current "status word" register. The functional conditions are usually a combination of computer-stored data and the physical condition or position of the gaging equipment. The computer then compares the current "status word" with a previously stored "proper status word" for that operation. Any deviation between the two will cause an operating program to abort and print a message notifying the operator of the incorrect condition. (See Figure 4 for an example of a typical "status word" for dedicated gages.)

The computer usually does not control the gage motions in this type of application; but, through

145050

Figure 1. COMPUTER CONTROL CABINET.

Figure 2. DEDICATED GAGE.

145059

Figure 3. SYSTEM CONTROL PANEL.

the use of the "status word", enables the collection and manipulation of data from one or more gages within a system. These systems vary in size, complexity, and capacity of data handling, as noted in Figures 5 through 7.

Figure 4. STATUS WORD. (Dedicated Gage)

Figure 5. PRINCIPAL COMPONENTS OF ONE TYPE OF DEDICATED GAGING SYSTEM.

As mentioned earlier, error correction due to part misalignment with respect to the basic machine parameters is a function that the computer is capable of handling in "realtime" providing the proper algorithms are available. Considerable work has been accomplished in this field for use with the small digital computer, such as Digital Equipment Company's "8" series.^(b) Figures 8 through 10 emphasize how the basic error corrections for part setup misalignment have been separated into three options. These options may be combined as required.

(b) Bookhart, T. W.; *Data Collection and Correction on a Computer-Controlled Dimensional Inspection Machine*, Y-EC-156; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; November 14, 1972.

Figure 6. PRINCIPAL COMPONENTS OF A SECOND TYPE OF DEDICATED GAGING SYSTEM.

The advantages of using a computer with dedicated gages becomes quite apparent after this chain of software development. The one remaining objective was to obtain higher gaging precision and accuracy, but with less precise, therefore cheaper, mechanical hardware. To obtain this objective it was necessary to develop transducers of a physical size, range, and accuracy approaching that of the state of the art.

Transducer systems were developed that did meet the requirements. Appendix A contains a typical specification for such a transducer system.

The resultant gaging systems produce data of a higher quality and at a lower per-piece cost than had been obtainable up to this time. The electronic and mechanical equipment costs

Figure 7. PRINCIPAL COMPONENTS OF A THIRD TYPE OF DEDICATED GAGING SYSTEM.

for these systems were normally less than that of the higher-quality hardwired mechanical systems. Where they were not, the savings in operational costs of the computerized systems offset the additional equipment costs in less than one year.

NUMERICALLY CONTROLLED, COMPUTER-ENABLED MACHINES

This application of the digital computer is an example of indirect computer control of an existing gaging or machining system for use in dimensional inspection of parts of revolution. Two examples are given in Figures 11 and 12.

The first example demonstrates the marriage of a digital computer to an existing numerically controlled measuring machine. The advantages gained through this application are those primarily of automatic data handling, including error correction and digital data output, as well as a decrease in utilization of such high maintenance items as strip-chart recorders and tape readers.

Figure 8. ONE-DATUM-DIAMETER CASE.

Figure 9. DATUM-SURFACE AND DATUM-DIAMETER CASE.

Figure 10. TWO-DATUM-DIAMETER CASE.

144152

Figure 11. MARRIAGE OF A DIGITAL COMPUTER TO AN EXISTING NUMERICALLY CONTROLLED MEASURING MACHINE.

Normal NC positioning data are stored in the computer memory along with special instructions for data handling. Positioning data only are fed to the NC unit, as necessary, during the inspection cycle.

The computer operating program contains all of the special subroutines necessary for inspecting various part features and are activated by use of an "M" code input with the part-type positioning data. "M" codes and their function are as follows:

M00 Stop, clamp slides.

M02 Clamp, rewind.

M10 Do one average cycle in the current inspection mode. (This cycle consists of 8 steps.)

Figure 12. ARRANGEMENT FOR PROVIDING SYNCHRONIZATION AND COMMUNICATION BETWEEN A CUTTING MACHINE AND ITS MEASUREMENT SYSTEM.

1. Position machine to the requested Y and Z coordinates.
2. Clamp the slides.
3. Output heading if requested.
4. Output tolerance.
5. Start table rotation for average cycle.
6. Calculate the average and output the results.
7. Check the results against the selected tolerances and accept or reject.
8. Check the machine mode. If in the auto mode, read and process the next block of part tape; if not in auto mode, wait for operator action.

M11 Continue.

M15 Set the error sign convention to indicate "+" as an increase in stock. This function also causes "OC" headings if no other mode is set.

M16 Set the error sign convention to indicate "-" as an increase in stock. This function also causes "IC" headings if no other mode is set.

M30 Rewind tape.

M51 Output "DATUM" as the heading and use the next M10 average cycle as a datum. This function causes all 256 of the error readings to be saved in a datum buffer for use in calculating the concentricity of a part.

M52 Output "Concentricity" as the heading and set the mode to concentricity. This function causes the data processing routine to make the following substitution:

$$\text{error} = \text{error} - \text{datum},$$

where "error" is the current error reading and "datum", the corresponding stored datum error.

After this substitution, the data are processed exactly like a latitude sweep. The output indicates high, low, TIR, and average.

M54 Sets up the flatness mode. The "FLATNESS" heading is output, and the high and low for each sweep are saved. After all the flatness sweeps have been run, an M55 block causes the flatness to be output.

- M55 Causes the high-low buffer to be searched for the highest high and lowest low. The TIR is calculated from these two values using the following equation:

$$\text{TIR} = \text{HIGH} - \text{LOW} .$$

The heading "TIR ON ABOVE SWEEPS" is output followed by the high, low, and TIR. M55 was designed to be used with an M54 for flatness calculations, but it is not limited to this application. Everytime the inspection mode is changed, the high-low buffer is initialized. The high and low for every sweep are saved in this buffer until the mode changes again. This sequence means that the TIR across several contour sweeps could be obtained by following the last sweep with an M55 block.

- M57 Causes "PARALLELISM" headings to be output. The data are processed exactly like a contour sweep. TIR can be obtained by using an M55 block.
- M58 Causes "LENGTH" headings to be output. The data are processed by the contour sweep routines.
- M59 Causes the contour mode to be set. This function causes an "IC" heading if the last sign M code was M16. If M15 or no sign M code appeared before the M59, the heading will be "OC". This code is not needed if the tape contains none of the other modes since the mode defaults to contour each time a new tape is read. It must be used to force a heading if setup correction is used in the tape (ie, M91 - 97).
- M60 Turns on the high-low tolerances. This function is defaulted each time a tape is loaded, which means that if a high-low is not required, an M61 must be used to turn it off before the first sweep.
- M61 Turns off the high-low tolerance requirement.
- M62 Turns on the average tolerance requirement.
- M63 Turns off the average tolerance requirement.
- M64 Turns on the TIR tolerance requirement.
- M65 Turns off the TIR tolerance requirement.
- M91 This M code is used for Type I correction and causes a sweep of a datum diameter. Data from this sweep determine the x and y offset.
- M92 This M code is used to sweep the datum surface of a Type II part. The tilt and vertical offset are determined from the data.
- M93 This sweep runs the datum diameter of a Type II part. The readings are corrected for tilt and vertical offset. Data are used to determine the x and y offset of the part.

- M94 This sweep determines the center of one of the datum diameters of a Type III part.
- M95 This sweep determines the center of the second datum diameter of a Type III part. A vector is then constructed through the centers of the two datum diameters. This vector is then used to determine the tilt and x and y part offsets.
- M96 This sweep determines the center of one of the datum diameters of a Type IV part.
- M97 This sweep determines the center of the second datum diameter of a Type IV part. These data, along with the data from the M96 sweep, determine the part tilt and x and y offsets.
- M98 This sweep runs the datum surface of a Type IV part and corrects the readings for tilt and offset. The data are then used to calculate the vertical offset.

Unfortunately, an NC "cutting" machine is not normally equipped to recognize all the codes used by an inspection controller during an inspection sequence. The solution to this problem is to wire the I/O bus of the computer in parallel with the NC unit's tape reader output. Installation via a switch was done so that either the hardwired NC unit's tape reader or the digital computer could input data to the machine's drive circuitry. A complete inspection part tape is read into the computer memory where software decodes each command. Only those commands needed for machine positioning are recoded in the cutting machine language and processed through to the NC system via the I/O bus. It, therefore, appears to the NC unit as if the commands originated from its tape reader. Thus, communications between systems utilizing vastly different levels of language sophistication have been achieved through the use of software.

In both instances, the versatility of the computer as a control link to an existing hardwired NC system was achieved without disabling the original controller and provided the desired data-handling capabilities at a cost far below that of a new acquisition. It should be pointed out that, in these two cases, the basic required mechanical accuracies were existing; but, had they been lacking, subroutines would have been developed that would correct for machine errors.

COMPUTER-CONTROLLED MEASURING MACHINES

Use of the digital computer for gage control and data handling of general-purpose gages presents an opportunity for economics not available with the conventional NC hardwired measuring equipment, when viewed in the overall manufacturing process.

Several years ago, when it became apparent that the inventory of existing general-purpose equipment would not meet the capacity requirements of today, several engineering studies were initiated. The purpose of these studies were threefold:

1. Determine what percentage of existing equipment would be suitable for today's production, from a maintenance and accuracy standpoint.
2. Determine today's inventory requirements with recommendations to upgrade existing equipment and/or purchase new equipment.
3. Insure that any combination of actions taken would guarantee a viable inventory of equipment five years from now.

The then existing inventory, when reviewed in these studies, indicated conditions that made it advisable to use all three options. At the same time, these studies indicated that it would be economically advisable to computer automate 70 percent of the total capacity expansion effort.

In light of the purpose of this report, only two of the projects involved will be briefly discussed.

Radius-Theta Gaging

The existing inventory of rotary contour gages (Rotacons) varied in age from three to nine years, and 85 percent were of the manually operated variety. Examples of the manually and NC hardwired operational equipment are given in Figures 13 and 14.

Production capacity requirements for the present time required an increase equal to four existing machines of an accuracy comparable to them when new.

Engineering studies indicated that two new computerized machines would provide the needed additional capacity, at a total cost below that of four manually operated machines. These conclusions were based on considerations which included the following:

1. Bid comparison between manually operated, hardwired NC machines, and softwired NC controlled machines.
2. Additional operating costs of manually operated machines.
3. Additional facilities required to support the two new machines.
4. Adaptability of equipment for future utilization and semiautomated process control and data handling.

Figure 15 provides views of the installed computerized equipment. A description and some features are highlighted in Appendix B.

Cartesian Coordinate

Two-Axis Measuring Machines - The existing two-axis measuring machines were from four to six years old; and, like the rotary contour gages, had proven to be the work horses of the department. Production schedules indicated a required increase in capacity of 180 percent. Figure 16 shows an existing machine of that time period.

136068

Figure 13. UPGRADED ROTARY CONTOUR GAGE.

Investigation and evaluation indicated that 60 percent of the existing inventory would not be viable for use today, resulting in a required capacity increase of 240 percent. Engineering studies showed that it was economically feasible to upgrade the existing machine mechanically and computerize their controls, with an expected increase in capacity of 50 percent. Evaluation of bids from gage manufacturers indicated that the remaining capacity could be procured by the purchase of five computerized two-axis machines at a cost less than that of hardwired numerically controlled machines with the required data handling capability.

The total effort was divided into two major portions: first, mechanically upgrade and computerize the existing equipment, by Y-12 Plant personnel; second, initiate a combined effort of the gage manufacturer and Y-12 Plant personnel to produce new, computerized gaging systems.

The upgraded and new equipment have exceeded design expectations, with a resulting increase in capacity of 200 percent instead of the postulated 150 percent. Views of the upgraded equipment as well as the new acquisitions are provided in Figures 17 and 18.

124675

Figure 14. NUMERICALLY CONTROLLED ROTARY CONTOUR GAGE.

Six-Axis Measuring Machines - The six-axis measuring machine (6-Co) inventory was seven years old at the start of the expansion project. Their control and drive hardware were those of the late "fifties"—very obsolete and excessively expensive to maintain.

Production requirements dictated that an equivalent capacity be available during the present time frame; therefore, a decision was made to have the existing machines rebuilt by outside gage manufacturers.

Response from gage manufacturers to this project was poor and their estimates were very high (approximately \$600,000 per machine).

Further studies indicated that mechanical upgrading and computerization, by Y-12 personnel in conjunction with an outside control vendor, of an existing partially completed machine would be less expensive and meet the capacity requirements.

Experience gained from similar mechanical projects was utilized in conjunction with a softwired controller purchased from an outside vendor.

(a) View 1.

(b) View 2.

146847
Figure 15. A LASER INTERFEROMETER ROTARY CONTOUR GAGE.

146945

Figure 16. TWENTY-INCH Y-Z MACHINE.

110257

Figure 17. UPGRADED 15 BY 20-INCH TWO-AXIS INSPECTION MACHINE.

147346

(a) View 1.

136063

(b) View 2.

136065

Figure 18. FORTY-INCH Y-Z MACHINE.

The resulting gaging system, seen in Figures 19 through 21, has met all expectations and provides a capability beyond that which would have resulted from rebuilding the existing machines.

149059

Figure 19. COMPUTERIZED SIX CO MACHINE.

The original machines were point-to-point six-axis controlled systems, while the new version is a seven-axis continuous-path inspection system capable of mechanical and dynamic-error correction if needed in the future, as well as possessing all developed data handling and part setup error functions. Appendix C provides lists of additional "M" and "G" codes used with this system.

One of the interesting features of this control system is that all servo positioning loops and interpolation are accomplished with software.

Further information about this control system may be found in Document Y-DN-16, *Computer-Controlled Machines for Dimensional Inspection Applications*, by H. S. Schwartz.

149060

Figure 20. CONTROL CONSOLE FOR THE COMPUTERIZED SIX-CO MACHINE.

Figure 21. COMPUTER AND AUXILIARY COMPONENTS.

CONCLUSIONS

As has been indicated, the use of small digital computers in conjunction with dimensional inspection processes is comparatively new and yet offers possibilities in the future to obtain higher precision with greater throughput at a reduced per-part inspection cost.

The primary factor considered in making decisions to automate with small digital computers was that of economics—original capital cost as well as operational costs for the first two years of operation.

Secondary factors such as increase in capability of functions and ease of future adaptations were considered, but only after the economics proved desirable.

Therefore, all systems were designed with the capability of interfacing with future planned projects involving the complete manufacturing process.

A third set of factors, not considered at this time, was that metrication appears to be possible with a minimum of effort.

ACKNOWLEDGEMENTS

The author wishes to thank H. S. Schwartz and J. P. Konopka of the Y-12 Dimensional Inspection Department as well as T. W. Bookhart for their assistance in the preparation of this report.

APPENDIX A

TYPICAL SPECIFICATIONS FOR A LINEAR DISPLACEMENT MEASURING SYSTEM

General

System is to include 48 displacement transducers of the linear variable differential transformer type, 48 amplifiers, detector modules, a high-level 48-channel multiplexer, a digital voltmeter, and printer.

Each displacement transducer will have its own amplifier detector module.

The system will be used to digitize and record linear displacements or to digitize and supply measurement data to other equipment.

Specifications for individual components of the system are as follows:

Displacement Transducer

Displacement transducer shall conform to Y-12 Materials Specification 06-MK-001 and Data Sheet 10P200AA.

Digital Voltmeter (DVM)

Number of Digits	Four digits plus sign. +99.9 to -99.9 with overrange digit.
Output Code	Binary coded decimal (BCD) to be available at a connector for use in other equipment (in addition to printer). Mating connector shall be provided.
Output Voltage	Zero volt for false level and +3V for true level.
Start Reading Signal	Reading to be initiated by a pulse or level change from 0 to +3V or from +3V to 0V. Seller shall describe signal requirement and shall make signal point available on a connector.
End of Conversion (EOC) Signal	The DVM shall signal EOC by a level change or pulse from 0V to +3V or from +3V to 0V. Seller shall describe EOC signal. EOC signal shall be made available at a connector for use in equipment external to the measuring system.

Printer

Number of Columns	Nine, min.
Printer Actuation	To be initiated by EOC signal from DVM with provisions for turning printer off when desired.

Printer Format $XY\pm ZZZ.Z$. X will be either I, O, or W as encoded by external equipment. YY will be a two-digit channel identification supplied by the Company. $\pm ZZZ.Z$ will be measurement data obtained from the DVM.

Multiplexer Relays

Number of Channels Forty eight, min.

Relay Contact Wiring Multiplexer relay outputs are to be wired in two groups of 24 contacts. The output of each group of 24 is then to be wired through an additional relay contact. The output sides of these two contacts are to be jumpered together and furnished to the DVM.

Multiplexer Controls None required.

Multiplexer Relay Coil Wiring The control side of each relay coil shall be wired to a connector for external control. The common side of all relay coils shall also be wired to the connector. A mating connector shall be provided. Diode protection shall be provided per Figure A-1.

Difference Amplifier

Outputs of the groups of 24 relays shall be subtracted through a difference amplifier (see Figure A-1). The output of the difference amplifier is to be switched through relay contacts to the DVM.

Zero and Gain Controls

Each amplifier-demodulator shall have a zero shift control and a magnitude control. Controls are to be hand adjustable. Controls shall be easily accessible to a maintenance technician but not readily accessible to operating personnel. Gaining access to Zero and Gain controls shall not disturb the environment of the amplifier demodulators.

Zero Shift 0.010 in.

System Specifications

Sampling Speed Minimum of 200 samples per second exclusive of printer. Minimum of two samples per second with printer on.

Linearity* 0.075% (includes only gage head & amplifier-demodulator).

Accuracy 0.15% at output of DVM over period of 30 hours (after warmup).

*Linearity is defined in Y-12 Materials Specification 06-MK-001.

Ambient Temperature $68^{\circ}\text{F} \pm 5^{\circ}\text{F}$.

Frequency Response 20 Hz, with a single gage head selected.

Input Connectors Amphenol Type 165-16 square flange receptacle shall be used at the system chassis for gage head signals.

INSPECTION AND TESTS

Tests at Seller's Plant - The equipment shall be inspected and tested to show full compliance with the specifications. The Seller shall submit a description of the inspection and test procedures with the bid. The Seller shall notify the Company 10 days prior to the commencement of tests. Certified inspection and test results shall be furnished to and approved by the Company prior to checkout at Seller's plant by the Company.

Figure A-1. DIFFERENCE AMPLIFIER.

Approved For
Procurement *E. J. R.*

06-MK-1
May 26, 1971
Page 1

A Materials Specification

UNION CARBIDE CORPORATION NUCLEAR DIVISION

U. S. Government Contract W-7405-eng-26

TRANSDUCERS--LINEAR DISPLACEMENT, PRECISION GAGING, LVDT

1. SCOPE AND CLASSIFICATION

1.1 Scope. This specification covers linear displacement transducers employing linear variable differential transformers for use in precision gaging. It was prepared for the types of linear variable differential transformers used by the UCC-ND Y-12 Plant Inspection Engineering Department.

1.2 Classification. Transducers covered by this specification are of three styles.

Style M - Stylus mechanically actuated (extended by spring).

Style P - Stylus pneumatically actuated (pressure extended, vacuum retracted).

Style PM - Stylus actuated by a combination of pneumatic and mechanical forces (extended pneumatically, retracted by spring).

2. APPLICABLE SPECIFICATIONS, STANDARDS, AND OTHER PUBLICATIONS

2.1 At the time of preparation, no other specifications or standards were considered applicable.

3. REQUIREMENTS

3.1 Material Requirements. The transducer stylus shall be constructed of nonmagnetic stainless steel. The barrel shall be of mag-

netic stainless. No brass, bronze, or silicone materials may be used in the cartridge, dust cover, or cable. No silicone may be used in the connector.

3.2 General Requirements.

3.2.1 Cabling and Connectors. Cable connectors for the P and PM styles (See Figure III) will be equipped with an air inlet adaptor and cable for carrying the pneumatic as well as the electrical signals to the transducer.

3.2.2 Dust Cover. A dust cover or rubber boot will be required if called for on the data sheet. Its purpose is to protect the stylus bearing surfaces from abrasive atmospheres. The dust cover does not cover the ball tip.

3.2.3 Non-rotating Stylus. The stylus shall be of a non-rotating design.

3.3 Detailed Requirements. A coded data sheet(s) forms a part of this specification. The required values and tolerances of the various parameters are specified on these sheets. The system for coding the data sheets is as follows:

The first digit(s) gives the total stylus travel in tenths of inches. The letter(s) following signifies the style of transducer. The second set of digits gives the gaging range of the transducer in thousandths of inches. The last two letters distinguish transducers within a group. A group is comprised of transducers with the same total stylus travel,

¹For use by installations in Oak Ridge, Tennessee and Paducah, Kentucky operated for the U. S. Atomic Energy Commission.

06-MK-1
Page 2

same style, and the same gaging range; but differing in at least one other parameter value.

3.4 Marking. Each transducer shall have the manufacturer's name or trade mark, date of manufacture, and the data sheet code electro-etched on the barrel of the transducer.

3.5 Final Acceptance. The final determination of compliance with the provisions of this specification shall be made by the Union Carbide Corporation, Nuclear Division's Standards Laboratory.

4. SAMPLING, INSPECTION, AND TESTING

4.1 Sampling and Inspection. All transducers will be inspected visually and dimensionally by UCC-ND for compliance with this specification. They will be inspected for defects in materials and workmanship which adversely affect the performance of the transducer.

4.2 Testing. Each transducer will be tested for compliance with all the requirements of this specification. The following definitions and explanations shall apply.

4.2.1 Output Voltage. Output voltage is the R.M.S. secondary voltage as measured at the

output cable plug. The measurement will be made with rated excitation voltage. The secondary windings are connected series opposing.

4.2.2 Null. The position of the stylus which gives zero or a minimum output voltage is defined as the null position, and the corresponding output voltage is the null voltage.

4.2.3 Axial Alignment. Axial alignment is the geometrical relation between the major axis of the barrel, stylus, pitch diameter of the internal stylus threads, and center of the ball tip.

4.2.4 Pre-travel. The initial travel of the stylus starting from a fully extended position and continuing to the gaging range is called pre-travel.

4.2.5 Over-travel. The initial travel of the stylus starting from a fully retracted position of the stylus and extending to the gaging range is defined as over-travel.

4.2.6 Gaging Range. The useful portion of the transducer response to stylus movement is the gaging range. It separates the pre-travel and over-travel regions. Numerically, it is the sum of the absolute values of the plus and minus ranges.

4.2.7 Total-travel. Total-travel is the sum of pre-travel, gaging range, and over-travel.

4.2.8 Linearity. Linearity is defined as the maximum deviation of the output voltage ratio curve from a straight line through the origin and lying parallel to the least squares best fit straight line. Linearity is expressed in percent as shown in Figure I.

Figure I

$$\% \text{ Linearity} = \frac{|y_i \text{ max.} - mx_i|}{mx_{\text{full range}}} \times 100$$

Where:

Line AB = Straight line through origin and parallel to best fit straight line.

$$mx_{\text{full range}} = | + mx_{\text{max}} | + | - mx_{\text{max}} |$$

$mx_{\text{max.}}$ = Calculated value on straight line corresponding to maximum displacement from null.

$y_i \text{ max.}$ = Output voltage ratio at point of maximum deviation from straight line.

mx_i = Point on straight line corresponding to maximum deviation point.

06-MK-1
Page 4

If the summation of the displacement values for a collection of data points is zero, then the slope (m) of the least squares

best fit straight line for that collection of data points is given by the following equation:

$$m = \frac{\overline{x_1 y_1}}{\overline{x_1^2}} = \frac{\sum_{i=1}^n (x_i y_i)}{\sum_{i=1}^n x_i^2}$$

Where:

- n = Number of test data points
- x_i = Displacement values of the data points
- y_i = Output voltage ratio values of the data points
- $\overline{x_1 y_1}$ = Average product of the x and y coordinates of each data point
- $\overline{x_1^2}$ = Average of the squared values of the x coordinates of all data points

Displacements each side of null for determining linearity shall be 2, 5, 10, 20, 40, 60, 80, and 100 percent of the bilateral range.

4.2.9 Voltage Ratio. The output voltage ratio is defined as the ratio transformer

setting which corresponds to the LVDT voltage output for a specific LVDT displacement. The voltage ratio can be measured using a ratio transformer, a phase sensitive demodulator, and a D. C. meter. See Figure II for a simplified system block diagram.

FIGURE II

06-MK-1
Page 5

5. PREPARATION FOR DELIVERY

5.1 Packaging. Each transducer shall be individually packaged in a padded plastic box having a hinged cover and containing a packaged desiccant.

5.2 Package Marking. Each plastic box shall be marked with the UCC-ND specification number, data sheet coding, UCC-ND Stores Catalog Number when shown on Purchase Order or Letter Release, and the manufacturer's name or trade mark.

5.3 Shipping Containers. The packages shall be delivered in commercial containers that will insure acceptance and safe delivery by common carrier.

5.4 Marking of Shipping Containers. Each shipping container shall be marked with the following information:

Seller's name
UCC-ND specification number
Purchase order number
Letter release number (if any)

06-MK-1
Page 6

TRANSDUCERS---LINEAR DISPLACEMENT, PRECISION GAGING, LVDT

Transducer Cartridge

Cable Connector
For Styles P and PM

Wiring Schematic

Figure III

Approved For
Procurement *SM*

06-MK-1
Amendment 1
September 1, 1971

A Materials Specification

UNION CARBIDE CORPORATION NUCLEAR DIVISION

U. S. Government Contract W-7405-eng-26

TRANSDUCERS--LINEAR DISPLACEMENT, PRECISION GAGING, LVDT

This Amendment forms a part of Materials Specification 06-MK-1.

Page 6. Figure III - Transducer Cartridge

Add 0.125 ± 0.020 inches to the nut thickness for the hexagon nuts on the barrel of the cartridge.

Add 0.090 - 0.100 inches as the nut thickness for the hexagon nut on the stylus tip.

Add 0.185 - 0.191 inches as the dimensions across the wrench flats of the hexagon nut on the stylus tip.

ALL DATA SHEETS

Change the fifth item from the top in the left hand column to read:
"Thickness, hexagon nuts on barrel (inches)"

¹For use by installations in Oak Ridge, Tennessee and Paducah, Kentucky operated for the U. S. Atomic Energy Commission.

06-MK-1
10P200AADATA SHEET

Transducers--Displacement, Linear, LVDT

Cartridge length including extended tip (inches)	<u>6.00 ± 0.10</u>	Cable length (feet)	<u>6.0</u>
Cartridge diameter (inches)	<u>0.3745 ± 0.0005</u>	Cable type	<u>Plastic Covered 5/C Shielded & Stranded Modified</u>
Cartridge thread (inches)	<u>3/8 x 40</u>	Cable plug	<u>Amphenol 165-13</u>
Thread length (inches)	<u>1.0</u>	Cable connection (end or side)	<u>End</u>
Hex nut thickness (inches)	<u>0.125 ± 0.020</u>	Bend radius--max. bend	<u>3/8 inch</u>
Stylus tip (Replaceable)		Serrated male hose connector tube size (I.D. inches)	<u>1/8</u>
Material	<u>Tungsten Carbide</u>	Air inlet adaptor (per Sketch)	<u>1 Required</u>
Diameter (inches)	<u>0.15625 ± 0.0001</u>	Air bleed adjustment--socket head conical tip set screw (inches)	<u>6-32 x 0.3125</u>
Spherical tolerance T.I.R. (inches)	<u>0.000010</u>	Excitation voltage (Volts RMS)	<u>1.77</u>
Stud thread (inches)	<u>4-48 x 0.150</u>	Excitation frequency (kilohertz)	<u>3 - 10</u>
Stylus dust cover	<u>Not Required</u>	Output voltage at one half gaging range from null (Millivolts RMS)	<u>150 min.</u>
Axial alignment T.I.R. (inches)		Linearity, Percent (at 70 degrees plus or minus 5 degrees F.)	<u>0.05%</u>
Stylus with respect to barrel	<u>0.001</u>	Pre-travel (inches)	<u>0.002 - 0.005</u>
Pitch diameter internal stylus thread with respect to barrel	<u>0.001</u>	Gaging range, Min. (inches)	<u>0.200</u>
Ball tip with respect to barrel	<u>0.001</u>	Total travel (inches)	<u>1.00 ± 0.020</u>
Radial play of stylus measured at equator of ball with stylus fully extended (max. inches)	<u>0.0003</u>		
Tip force - ounces			
grams	<u>10 - 25</u>		
Air supply pressure, Max. (PSIG)	<u>5.0</u>		

Revised June 17, 1971

APPENDIX B

DESCRIPTION OF COMPUTERIZED EQUIPMENT

The AA Gage rotary contour gage (AA Rotacon) is a fully automated, computer-controlled measuring machine specifically designed for the simultaneous inspection of both inner and outer surfaces of revolution. Surfaces to be inspected do not necessarily require a constant radius, being concentric, or having a uniform wall (inner contour minus outer contour). Parts to be inspected can have an outer radius range from 0 to 9.75 inches and an inner radius range from 0.875 to 9.75 inches.

Table B-1

INDIVIDUAL AXES FOR THE AA ROTACON

Axis of Movement		Resolution	Min/Max Rate Velocity
Tilt	"c"	1 Arc Sec ⁽¹⁾	1/6 rpm (fixed rate)
Rotary Table	"b"	0.001 Degree	1/2 to 6 rpm (bidirectional)
Inner Slide	"X"	0.00001 Inch	0 to 2 ipm
Outer Slide	"U"	0.00001 Inch	0 to 2 ipm

(1) Modified from 5 arc sec of resolution under a separate contract in January 1973 by AA Gage.

The AA Rotacon has four, basic, closed-loop positioning axes of movement which are driven by an Inland torque motor (TT-1208B) and servo amplifier (EM-1804-00). A brief description of the individual axes is given in Table B-1.

The "c" axis system is located between two trunnion bearings (Figure B-1) which can be positioned from -2 to +92 degrees with respect to the inner and outer slides. Angular position sensing is made by a 12-inch, 720-pole rotary Inductosyn plate mounted directly to the right trunnion bearing. Also provided for is an absolute digital readout in degrees, minutes, and seconds (Figure B-2).

The "b" axis consists of a 24-inch-diameter, 360-degree ball-bearing rotary table which contains an encoder (29-2-004-2500 SV Pynam Research Co) used to provide angular readout information.

The "X" and "U" axes are comprised of electrojet holding devices mounted on recirculating ball slides (Figure B-3) which are perpendicular to the rotary table axis at a tilt portion of 90 degrees and parallel to the rotary table axis at a tilt portion of 0 degree. Linear displacement of the slides is measured by means of a Hewlett Packard laser interferometer (Model 5526A) with automatic corrections for the velocity of light, temperature, pressure, humidity, and part coefficient expansion.

Synchronization of the four basic positional axes in both the point-to-point and continuous-path inspection modes are computer programmed controlled. The "operating program", written by Control Logic Incorporated, allows the operator to select anyone of five different control modes: automatic, block by block, semiautomatic, manual, or jog.

In the automatic control mode, a "part tape" is punched for a specific part and is read into the computer via a tape reader. Part-tape format details are described in the discussion that follows.

149383

Figure B-1. AA ROTACON "c" AXIS SYSTEM LOCATED BETWEEN TWO TRUNNION BEARINGS.

Tape Format:

N3.g2.X 15.U15.c + 6.b + 32.f.h2.i.2.d14.314.m2

where:

N represents the sequence number,

*g the preparatory function,

X the inside radius (linear),

U the outside radius (linear),

c the tilt angle (rotary sweep),

b the table angle (rotary table),

- f the feedrate (inverse time),
- h the helix angle (degrees/revolution),
- i the cosine of the angular distance between C axis angle (measured from X - axis) and the part surface normal (measured from X - axis),
- d the inside part surface normal (measured from the X - axis),
- e the outside part surface normal (measured from the X - axis), and
- *m the miscellaneous function.

***g - codes**

- 01 - linear interpolation - motion
- 80 end of sweep - output average
- 90 - error correction routine
- 91 - error correction routine
- 96 - data block - no motion
- 97 - latitude control mode
- 98 - longitude control mode
- 99 - spiral control mode

***m - codes**

- 00 - program stop
- 02 - end of program
- 03 - rotate table clockwise
- 04 - rotate table counterclockwise
- 10 - turn sampling on for averaging
- 11 - turn sampling off for averaging
- 30 - rewind tape
- 60 - b axis: 360 samples/revolution

- 61 - b axis: 180 samples/revolution
- 62 - b axis: 90 samples/revolution
- 63 - b axis: 45 samples/revolution
- 64 - b axis: 18 samples/revolution
- 65 - b axis: 9 samples/revolution
- 66 - c axis: 6 samples/degree
- 67 - c axis: 3 samples/degree
- 68 - c axis: 2 samples/degree
- 69 - c axis: 1 sample/degree
- 70 - c axis: 1/2 sample/degree
- 71 - c axis: 1/4 sample/degree

Selection of random sequence numbers in the part tape by the operator can be made in the block-by-block mode. A group of console thumbwheel switches (Figure B-4) are available which will perform varied functions when initiated by the operator. The console thumbwheel switch labeled "sequence search" allows the operator to select random sequence numbers from 1 to 999 which are digitally displayed.

The semiautomatic control mode allows the operator to input data into the computer via the console thumbwheel switches (Figure B-4). The outer slide, inner slide, rotary table, and tilt angle can be commanded to any position within the range limits of each axis by simply dialing in the command position and depressing the button labeled "position". Digital readouts are provided for each axis either displaying the actual or command position. Selection of either position is made by depressing the button labeled "actual command" on each axis.

Manual and jog control switches are provided (Figure B-5). In this mode of control, the operator acts as the feedback element for both position and rate sensing for each axis. Axis rate control is provided for by using a potentiometer to vary the input voltage to each drive motor.

The latitudinal, spiral, and longitudinal sweep modes are initiated and terminated by various "g" codes which cause an interrupt to the computer. These interrupts cause a definite sequence of routines (subprograms) which control the four positional axes of the machine.

In the latitudinal sweep mode, the command information is entered into the computer by either a "part tape" in the automatic control mode or by operator thumbwheel switches in the semiautomatic mode. The "c" axis is positioned first to a particular angular degree (-2 to

145440

Figure B-2. ABSOLUTE DIGITAL READOUT FOR THE ROTACON.

920), followed by the individual positioning of the "X" and "U" axes to the command position. Part deviations are then measured by the inner and outer linear variable differential transformer (LVDT). Output data are then recorded either on a strip-chart recorder or printed out via the computer teletype (Figure B-6).

Command information is entered into the computer via the "part tape" in both the spiral and longitudinal sweep modes. The spiral sweep mode synchronizes the "b" and "c" axes to

149380

Figure B-3. ELECTROJET HOLDING DEVICES FOR THE ROTACON.

145464

Figure B-4. GROUP OF CONSOLE THUMBWHEEL SWITCHES FOR THE ROTACON.

follow a continuous spiral trace of a piece part starting at either the pole or equator of the part. Any helix angle between 1 and 10 can be selected by specifying the correct "h" factor.

The longitudinal sweep mode provides a continuous sweep of the "c" axis from either -2 to 92° or 92 to -2°, while the rotational "b" axis is held stationary. In both the spiral and longitudinal sweep modes, expected inner and outer contours (see Equation 9) are computed as a linear interpolation on the current tilt-axis interval. The position deviation of the inner and outer electrojets (LVDTs) and dynamic averages are displayed on either a strip-chart recorder or teletypewriter printout.

There are three routines in the "operating program" which perform the basic positioning of the four axes of motion: (1) positioning executive (2) rate output calculation, and (3) display position.

The "positioning executive" routine performs the following tasks:

145458

Figure B-5. MANUAL AND JOG CONTROL SWITCHES FOR THE ROTACON.

1. Calculates the current actual position.
2. Extracts data from the "tape data buffer" (storage element for part tape data) as required for movement to the next point (command position).
3. Calculates the position displacement (command minus actual position).

4. Maintains the "measurement interval table" (MIT) and the "command position table" (CPT).
5. Determines whether motion will be terminated after the next commanded position is attained.

149381

Figure B-6. COMPUTER TELETYPE PRINTOUT SYSTEM.

The current actual position is the location to which each axis is being servoed. Equation B-1 contains all the necessary parameters in order to calculate the current actual position for the latitude sweep mode:

$$X_i = X + O_b + E_{mx} , \quad (B-1)$$

where:

X represents the measured "X"-axis slide position,

O_b the offset as a function of the "b"-axis position,

E_{mx} the LVDT null offset from mastering, and

X_i the current actual position on the "X" axis.

The current actual position on the "U" axis is also computed using the same format as in Equation B-1. Current actual "b" and "c" axes positions are the measured values from the Inductosyn "c" axis system and the binary "b" axis encoder.

The position displacement " E_x " (see Equation B-2) is defined as the current actual position (X_i) less the command position (C_x). The sign of the result is the complement of the direction of motion to the command position:

$$E_x = X_i - C_x . \quad (B-2)$$

All four positional-axes displacements are computed as indicated, except for the "b" axis during positioning (see Equation B-3). When the "b" axis is holding its servoed position, the "b"-axis displacement is computed using Equation B-3, thus:

$$E_b = C_{b_{i-1}} - C_{b_i} , \quad (B-3)$$

where:

$C_{b_{i-1}}$ represents the previous commanded "b" axis position, and

C_{b_i} the current command "b" axis position.

The "rate output calculation" routine computes the rate of velocity on the "X", "U", and "b" axes, given the "position displacement" from the "position executive" routine, the current rate saved from the last cycle output, and the command feedrate from the "part tape" which is stored in the "master state table" (MST).

There are three interim rate calculations that are made in the spiral, longitudinal, and latitude sweep modes. These different rate calculations are computed in order to correct for acceleration and deceleration of the "X", "U", and "b" positional axes when motion is initiated or terminated.

Interim Rate Calculation 1 is based upon the linear function of the position displacement " E ", indicated in Figure B-7.

Constants stored in rate control table (V_1 , V_2 , a_1 , a_2 , β_1 , β_2 , E_1 , E_2) Interim Rate Calculation 2 is a function of the current rate (see Equation B-4):

Figure B-7. LINEAR FUNCTION OF THE POSITION DISPLACEMENT " E ".

$$V_b = V \div \Delta V_1 \text{ (acceleration factor) ,} \quad (\text{B-4})$$

where:

V represents the current rate constant, and

ΔV_1 the constant for $E > 0$.

$V_b = V - \Delta V_2$ for $E < 0$.

In Interim Rate Calculation 3, a feedrate number, "f", is designated on the "part tape" for determining the rate at which the axis should be moved to achieve coincident arrival at the command position:

$$f = \text{feedrate} = \left(\frac{1}{\text{time}} \right) \left(\frac{1}{\text{minutes}} \right) .$$

The rate velocity can be computed by using Equation B-5:

$$V_c = f \Delta P , \text{ and} \quad (\text{B-5})$$

$$\Delta P = P_c - P_o ,$$

where:

P_c represents the actual command on the current block of "part tape" being executed, and

P_o the actual command on the previous block of "part tape" having been executed.

The computer selects the minimum value of the three rates calculated ($V_{\min}$) and multiplies this value times a scalar gain factor. This digital information is then changed into an analog signal through use of a DA converter which drives the individual axis servo system to the command position in the latitudinal sweep mode.

In the spiral sweep mode, the "b" axis rate of velocity is a function of the "c" axis position displacement and the helix angle indicated on the "part tape".

The relationship between the "b" axis and "c" axis displacement is given by Equation B-6:

$$\Delta_b = \frac{\Delta_c}{h} \times 360 , \quad (\text{B-6})$$

where:

Δ_c represents the command "c" axis displacement,

h the helix angle from the "part tape", and

Δ_b the resulted commanded "b" axis motion in degrees.

In the spiral and longitudinal sweep modes of inspection, a dynamic correction factor (see Equation B-7) is applied to improve the tracking of the "X" and "U" axis slides in relationship to the "c" axis:

$$T_c \text{ (a correction factor)} \equiv (E_{x/m} - A_{x/m}) F_{x/m}, \quad (\text{B-7})$$

where:

$E_{x/m}$ represents the expected "X" or "U" value,

$A_{x/m}$ the actual "X" or "U" value, and

$F_{x/m}$ the empirical factor.

The expected value is computed by subroutine titled "Measurement Executive" which performs a linear interpolation (see Equation B-8) over the "c" axis interval defined in the Measurement Interval Table. The Linear Interpolation routine uses the first two spatial points in the Measurement Interval Table to define the interval containing the "c" axis position. In all the other modes of inspection except the spiral and longitudinal modes, the expected value is the command position.

$$E_{x/m} = E(\hat{c}_i) = \hat{f}(\hat{c}_i) - \left[f(c_k) + \frac{(\hat{c}_i - c_k)}{(c_{k+1} - c_k)} \left\{ f(c_{k+1}) - f(c_k) \right\} \right], \quad (\text{B-8})$$

[linear interpolation]

where:

$\hat{f}(\hat{c}_i)$ represents the measured x/u position at $\hat{c}_i$,

$\hat{c}_i$ the "c" axis entries in the MIT which defined the interval which includes $\hat{c}_i$, and

$f(c_{k+1})$ the x/u position in the MIT associated with c_k and c_{k+1} .

k is determined by $c_k < \hat{c}_i < c_{k+1}$.

The corrected rate velocity calculation for the "X" and "U" axes (see Equation B-9) in the spiral and longitudinal sweep modes is:

$$V_{\text{corrected}} \equiv [V_{\text{min}} + f_{x/u} (E_{x/u} - A_{x/u})], \quad (\text{B-9})$$

The $V_{\text{corrected}}$ rate velocity is then multiplied by a scalar gain constant and is converted to an analog signal by using a DA converter. The signal is then applied to the "X" and "U" axis servo systems.

The Rate Output Calculation routine connects the "c" axis rate into a "c" axis step (see Equation B-10) for a cycle of 16.6 milliseconds in all the automatic modes except the spiral sweep mode. An "h" divider is supplied on the "part tape" during a spiral sweep. The rate is converted to a fraction of the maximum rate (one rpm) and then applied to the "c" axis servo system.

$$\text{"c" axis rate} = \frac{1/f}{16.6 \text{ milliseconds} \times \Delta c}, \quad (\text{B-10})$$

where:

Δc^0 represents the (actual-command) position, and

f the feedrate number specified in the "part tape".

In the semiautomatic and manual modes, the "c" axis servo system is driven at the maximum rate of one rpm and the inner and outer servo systems in the semiautomatic mode are driven at a fixed rate of six inches per minute.

Table B-2
MINIMUM MECHANICAL MEASUREMENTS FOR THE STORED-
PROGRAM-CONTROLLED ROTARY CONTOUR GAGE

Axis	Mechanical Measurement	Accuracy	General Comments
"g"	Table Runout (radial) TIR	50 microinches	Either direction and at any angle of the "c" axis.
	Axial (TIR)	20 microinches	"c" axis at zero degrees.
	Flatness & Squareness	100 microinches	Total 24-inch table surface.
	Angular Positioning Command	30 arc seconds	Within any increment of 360°.
	Table Height Adjustment Parallelism of "X" and "U" Axes with "c" Axis Position to Zero Degrees	50 microinches	Half inch of adjustment.
"c"	Angular Positioning Command	5 arc seconds	Within any increment between -2 to 92°.
	Intersection Error between "c" Axis and "b" Axis	50 microinches (total bandwidth)	Either direction -2 to 92° or 92 to -2°.
"X" & "U"	Linear Position Command	25 microinches	In any increment between 0 - 10 inches of travel for outer slide and 0 - 4 inches of travel for inner slide.
	Perpendicularity of "X" and "U" Axes to "b" Axis with "c" Axis at 90°	200 microinches (TIR)	Full inner and outer slide travel.
	Tip Test	200 microinches	"c" axis displacement from 90 to 70°.
All Axes	Composite Test		
	A Master Part is Inspected a Total of 5 Times in all the Various Sweep Modes	Maximum unassignable cause. Allowable deviation of any one inspection shall be ± 100 microinches	Each inspection requires a total remastering of the gage.
	"c" Axis Hysteresis Error in Spiral & Longitude Sweep Mode	100 microinches	Bidirectional shift of the "c" axis when an inspection of a part is initiated at either the pole or equator of a part.

In the "manual" and "jog" modes, the inner and outer servo systems can be varied from zero to six inches per minute by using the potentiometer control shown on the panel of Figure B-5. Also shown are the "jog" controls for the "c" and "b" axes.

Listed in Table B-2 are the minimum static and dynamic mechanical measurements which were required for acceptance of the Stored-Program-Controlled Rotary Contour gage cited on Y-12 Specification 2516.

APPENDIX C

LISTS OF ADDITIONAL "M" AND "G" CODES

Additional "M" and "G" codes utilized for the continuous-path, computerized, six-coordinate measuring machine.

<u>M Code Words</u>	<u>Type</u>	<u>Description</u>
M00	Nonmodal	Program stop.
M01	Nonmodal	Optional stop.
M02	Nonmodal	End of program.
[M60	Modal	X Axis brake on
[M61	Modal	X Axis brake off.
[M62	Modal	Y Axis brake on.
[M63	Modal	Y Axis brake off.
[M64	Modal	D Axis LVDT extend.
[M65	Modal	D Axis LVDT retract.
[M70	Modal	U Axis brake on.
[M71	Modal	U Axis brake off.
[M72	Modal	V Axis brake on.
[M73	Modal	V Axis brake off.
[M74	Modal	E Axis LVDT extend.
[M75	Modal	E Axis LVDT retract.
[M80	Modal	B Axis brake on.
[M81	Modal	B Axis brake off.

Note: Codes within brackets are mutually exclusive to all other codes within that bracket (modal group).

<u>G Code Words</u>	<u>Type</u>	<u>Description</u>
[G00	Modal	Positioning Mode.
[G01	Modal	Linear Interpolation Mode.
G04	Nonmodal	Dwell.
[G28	Modal	Insert new axis value. Changes axis position registers to value programmed in block (no axis motion).
[G29	Modal	Cancel G28.
[G80	Modal	Cycle off, Sets all brakes to the "off" condition.
G97	Modal	Latitude sweep cycle. Sets the "b" axis brake off and all other axis brakes on.

<u>G Code Words</u>	<u>Type</u>	<u>Description</u>
G98	Modal	Longitude sweep cycle. Sets the "b" axis brake on and all other axis brakes off.
G99	Modal	Spiral sweep cycle. Sets all axis brakes to the "off" condition.
[G90	Modal	Absolute mode.
[G91	Modal	Incremental mode.
[G93	Modal	V/D feedrate program- ming (1/T mode).
[G94	Modal	Direct ipm feedrate programming.
G96	Nonmodal	Data block. Ignore all data in this block.

Note: Codes within brackets are mutually exclusive to all other codes within that bracket (modal group).

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