210/
11-7

2330

Y-1845

A POSITIONING-ERROR MEASURING SYSTEM FOR
NUMERICALLY CONTROLLED MACHINES

J. H. Burkhardt, Jr
C. M. Lay

**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*

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Reference to a company or product name does not
imply approval or recommendation of the product
by Union Carbide Corporation or the U S Atomic
Energy Commission to the exclusion of others that
may meet specifications.

**A POSITIONING-ERROR MEASURING SYSTEM FOR
NUMERICALLY CONTROLLED MACHINES**

J. H. Burkhardt, Jr
C. M. Lay

Oak Ridge Y-12 Plant

P.O. Box Y, Oak Ridge, Tennessee 37830

operated for the U.S. ATOMIC ENERGY COMMISSION
by UNION CARBIDE CORPORATION—NUCLEAR DIVISION
under Contract W-7405-eng-26

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Date Issued - October 18, 1972

MASTER

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

ABSTRACT

A system has been developed for measuring the static and dynamic positioning error of a numerically controlled machine slide. The actual slide position is determined with a laser interferometer and compared with the commanded position. Positioning error (the difference between the actual position and commanded position) is displayed on a strip-chart recorder. An analysis has been made of the system accuracy.

CONTENTS

SUMMARY	5
INTRODUCTION	6
ERROR MONITOR FOR NUMERICALLY CONTROLLED MACHINES	7
System Description	7
Component Description	8
Laser Interferometer	8
Fringes-to-Inches Converter	8
Resolution and Steering Logic	10
Anticoincidence Circuit	10
Data Output Circuitry	10
System Evaluation	12
Applications	12
ACKNOWLEDGEMENTS	18
APPENDIX	19
System Drawings	19

SUMMARY

An error measuring system was developed for measuring the positioning error of a numerically controlled machine tool slide. True slide position is determined with a laser interferometer and compared with the commanded position. Slide positioning error is determined by algebraically summing the machine command pulses and interferometer pulses. This error is displayed on a strip-chart recorder.

The system is designed for use on machines whose slides move 10, 20, or 100 microinches per command pulse. It can be used to measure the initial slide lag, cyclic error, dynamic positioning error, and static positioning error. An expression has been developed for determining the maximum error of the system.

INTRODUCTION

Numerically controlled (NC) machine-tool positioning systems are in use in the Oak Ridge Y-12 Plant.^(a) The positioning accuracy of these machines must be accurately measured and controlled while producing close-tolerance parts. Improvements in precision machining depend upon better methods of determining the machine parameters which affect the tool-path accuracy of the machine. Methods for determining the positioning accuracy using length standards and null meters are limited to point-to-point measurement and yield data that are useful, primarily, for static studies. The laser interferometer offers a faster, more accurate means of determining positioning accuracy; and, at the same time, reduces the sources of human error. However, as presently used, it too is limited to static or point-to-point measurements.

Dynamic errors such as cyclic error, following error, slide oscillation, and resolver phase cycling which affect machining accuracy and finish cannot be determined by point-to-point techniques. This report describes a system for measuring those parameters which determine the dynamic characteristics of NC machines.

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

ERROR MONITOR FOR NUMERICALLY CONTROLLED MACHINES

SYSTEM DESCRIPTION

Operation of the error monitor is based on the principle of measuring the difference between how far a machine slide should have moved and how far it actually moved. Most numerically controlled (NC) machines in the Oak Ridge Y-12 Plant are designed for 10, 20, or 100 microinches of slide travel per command pulse from its machine control unit (MCU). By counting these pulses, the commanded travel can be determined; actual travel is measured by counting the fringe pulses from a laser interferometer mounted on the slide. By making the value of the interferometer pulses and command pulses equivalent, their algebraic sum will represent the positioning error. A block diagram of the error monitor and a typical machine tool setup are given in Figure 1.

Figure 1. NUMERICALLY CONTROLLED ERROR MONITOR AND TYPICAL MACHINE SETUP.

A view of the control panel switches is presented in Figure 2. The "reset" button is used to initialize the logic and return the output to the zero error position. The "range" switch is used to select a system resolution of 12.5, 25.0, or 125 microinches corresponding to a 10, 20, and 100-microinch resolution machine, respectively. Figure 3 shows the physical arrangement of the power supplies, fringes-to-inches converter, and logic cards. Complete logic diagrams are presented in the Appendix.

Figure 2. NUMERICALLY CONTROLLED ERROR MONITOR SYSTEM CONTROL PANEL.

141329

COMPONENT DESCRIPTION

Laser Interferometer

Two types of laser interferometers can be used with this system. Each has a characteristic wavelength (λ) of 24.91438 microinches for average Y-12 machine shop environmental conditions. One type of interferometer has two outputs, A and B, that are quadrature positive logic signals. Each level transition of Output A represents a slide motion of $\lambda/4$. Direction of the slide motion determines the phase relationship of A and B. The second type of interferometer has up-and-down pulse outputs. The pulses are positive transistor-transistor logic (TTL), compatible with a width of 40 nanoseconds. When the slide has moved $\lambda/4$ in one direction, one more pulse will have appeared at the output, representing motion in that direction, than at the other output. It is important to note that the digital outputs from both interferometers are not compensated for changes in temperature and atmospheric pressure.

Fringes-to-Inches Converter

Prior to entering the fringes-to-inches converter, the pulses from the pulse-type interferometer are divided by two. This action converts the pulse resolution from $\lambda/4$ to $\lambda/2$ and makes it compatible with the fringes-to-inches converter.

Figure 3. NUMERICALLY CONTROLLED ERROR MONITOR ELECTRONICS CHASSIS.

141331

The fringes-to-inches converter^(b) converts the interferometer signals to up-and-down pulses of 12.50 microinches. This circuit is designed to be used with laser interferometers having

(b) Lay, C. M.; *Fringes-to-Inches Converter for Interferometric Measurement and Control*, Y-1655; Union Carbide Corporation-Nuclear Division, Oak Ridge Y-12 Plant, Oak Ridge, Tennessee; January 23, 1969.

a stable wavelength of 24.91438 microinches. Some additional error will be introduced by the converter if the wavelength differs from the design value.

Resolution and Steering Logic

The resolution logic blocks out every fifth command pulse. This step results in a modified command pulse of 12.5, 25, or 125 microinches for an input pulse of 10, 20, or 100 microinches, respectively.

The value of the interferometer pulse is changed to match that of the modified command pulse. A rate divider controlled by the range switch (see Figure 2) is used to generate one output pulse for every 1, 2, or 10 input interferometer pulses (from the fringes-to-inches converter). These modified interferometer pulses then have values of 12.5, 25, or 125 microinches, respectively, making them equivalent to the modified command pulses. Conversion of the command pulses is automatic, but the range switch must be set according to the resolution of the machine being tested.

Direction information is provided by the level of the direction signal in the MCU. It will assure that interferometer pulses, representing motion in the commanded direction, always appear on the +I line and that interferometer pulses, representing motion in the opposite direction, always appear on the -I line.

Anticoincidence Circuit

Purpose of the anticoincidence circuit is to separate the two interferometer signals and command signal and generate up/down pulses to the bidirectional counter.

A logic diagram of this circuit is outlined in Figure 4. A command pulse or interferometer pulse will set the appropriate flip flop (FF4, FF5, and FF6). A strobe pulse then alternately resets these flip flops and generates a 50-nanosecond up-or-down pulse.

Timing of the strobe clock is critical in that it must be adjusted low enough to prevent an overlap of the 50-nanosecond up/down pulses yet high enough to clear the storage flip flops before the arrival of succeeding data pulses. A free-running 13-MHz clock provides the basic frequency. This frequency is divided in half by a flip flop which produces a 7.5-MHz square wave. This square wave and its complement are used to strobe the storage flip flops. Being strobed by complementary square waves, the command storage flip flop and the interferometer storage flip flops will be reset alternately, thus separating the up/down pulses by the period of the strobe signal.

Data Output Circuitry

Up/down pulses from the anticoincidence circuit are applied to the inputs of a 10-bit synchronous bidirectional binary counter. The digital output of the counter is fed to a commercially available 10-bit bipolar digital-to-analog converter whose bipolar 10-volt output is recorded on a strip-chart recorder. A positive voltage indicates that the slide is lagging the commanded position; a negative voltage indicates that the slide is ahead of the commanded position (as in overshoot).

Figure 4. ANTICOINCIDENCE CIRCUIT.

SYSTEM EVALUATION

The system output (E_O) may be expressed as:

$$E_O = E_m + \epsilon_\lambda + \epsilon_F + \epsilon_s + \epsilon_D + \epsilon_R ,$$

where:

E_m represents the true machine slide error,

ϵ_λ the error introduced by a change in the interferometer wavelength

$$\left(\frac{\lambda - 24.914380 \times 10^{-6}}{\lambda} \frac{\text{inches}}{\text{inches of slide travel}} \right) ,$$

ϵ_F the error introduced by the fringes-to-inches converter

$$\left(\pm 6.25 \mu\text{in} + \frac{0.16 \text{ microinch}}{\text{inch of slide travel}} \right) ,$$

ϵ_s the error due to limited interferometer resolution and various scaling circuits
 (- 1.25 command pulses, maximum),

ϵ_D the error introduced due to the DAC nonlinearity (± 0.625 command pulse, maximum), and

ϵ_R the error of the strip-chart recorder (typically $\pm 0.25\%$ of full scale, maximum).

The error monitor system was tested using a pulse output interferometer on a horizontal, two-axis, numerically controlled turning machine. The environmental conditions resulted in an ϵ_λ of + 0.8 microinch per inch of slide travel (see Figure 5). The strip-chart recorder was operated with a span equivalent to 125 command pulses, giving an ϵ_R of ± 0.313 command pulse. This value produces a theoretical maximum system error for these tests of + $[0.938 + (1/C_p)(6.25 + 0.96 T_s)]$, or - $(2.138 + 6.25/C_p)$ command pulses, where T_s represents the slide travel in inches, and C_p the command pulse value in microinches.

A series of static positioning tests were made to check the error monitor accuracy. A typical strip chart of this static positioning error is given in Figure 6. After each 0.1-inch step, the interferometer readout was recorded and the commanded position subtracted to give a calculated error. A comparison of the calculated slide error and chart data is summarized in Table 1. The experimentally measured system error is well within the theoretical limits.

APPLICATIONS

The dynamic-error measuring system can be used to observe the dynamic performance of a machine as well as to obtain data useful in dynamic error correction and machine maintenance. Instantaneous-positioning error, following error, slide-velocity variation, cyclic error, and slide response can be measured and recorded directly. These data may then be used to predict the contouring accuracy of the machine. Slide oscillation, excessive dynamic

Figure 5. A FRINGE-LENGTH GRAPH OF A 6328-ANGSTROM, NEON-20 LASER IN DRY AIR (0.03% CO₂).
(From Perkin-Elmer Laser Products Department)

Figure 6. TOOL-SLIDE STATIC POSITIONING ERROR AT 0.1-INCH INCREMENTS FOR A 10-MICROINCH-RESOLUTION HORIZONTAL LATHE THAT IS OPERATING AT A FEEDRATE OF 1/2 INCH PER MINUTE. (Chart Speed = 1 ipm)

Table 1
SUMMARY OF RESULTS FOR STATIC
POSITIONING ERROR DATA
(Errors are Expressed in Microinches)

Calculated Slide Error	Monitor Indicated Error	System Error
- 30	- 37.5	- 7.50
0	0	0
- 30	- 41.2	- 11.20
+ 10	- 2.5	- 12.50
+ 10	+ 1.2	- 8.80
- 30	- 25	+ 5.00
+ 10	0	- 10.00
- 10	- 12.5	- 2.50
+ 20	+ 12.5	- 7.50
+ 30	+ 32.5	+ 2.50

positioning error, resolver phase cyclic error, and "hunting" caused by faulty or improperly adjusted electrical or mechanical components can also be readily determined from the same recorded data. This information is extremely helpful in diagnosing mechanical and/or electrical maintenance problems. These positioning error data may also be used to determine mechanical or electronic compensating cam configurations. Error compensation based on this information is inherently more accurate since it is dynamic and continuous instead of a point-to-point measurement and discontinuous.

Figure 7, Part (a) provides an error chart of a machine slide with excessive oscillation caused by a broken tachometer coupling, resulting in an under-damped system. The screw cyclic error peaks are also influenced by slide oscillation. This condition would cause a poor surface finish on the part being machined and would also subject the machine members to harmful vibration and strain. Figure 7, Part (b) is a chart of the same machine with the oscillation corrected.

(a) Chart for a Machine with a Broken Tachometer Coupling

(b) Chart with the Condition in View (a) Corrected and Illustration of Following Error Measurement

Figure 7. ERROR CHARTS OF A MACHINE SLIDE.

Charts, such as shown in Figure 7(b), can also be used to check machine control adjustments. The loop gain and velocity feedback are normally adjusted for a following error of 1.0 mil per inch per minute of feed rate, while the actual error recorded is 1.25 mils per inch per minute. This discrepancy is caused by an error between the commanded and actual feed rates. When the feed-rate error is not the same on both axes (and it seldom is), the actual tool path will be skewed from the programmed tool path instead of being on the contour and the correct predetermined amount behind the commanded position.

The chart in Figure 8(a) was obtained on a machine slide with both an excessive screw cyclic error and with a cyclic error superimposed upon it due to poor quadrature relationship of the resolver excitation signal. This condition would also affect the surface finish and contouring accuracy. The screw cyclic error is caused by screw eccentricity. The quadrature phase relationship of the resolver excitation signal was adjusted (to about 90°) until the superimposed cyclic error disappeared. The damaged screw and bearings of this machine were also replaced to correct the screw cyclic error. Figure 8(b) shows the slide error after replacing the screw but before readjusting the excitation signal phase; Figure 8(c) shows the error with both problems corrected.

Figure 8. ERROR CHARTS OF A MACHINE SLIDE WITH TWO TYPES OF ERROR.

The dynamic method of measuring and recording machine errors is superior to previous methods. The data, being dynamic, allows for a better qualitative analysis of machine performance. Data can be obtained faster and easier with no special programming of the machine since the slides can be moved continuously with the manual feed controls. Some

facility must be gained in interpreting the recorded information, keeping in mind that the chart trace contains those dynamic quantities just described.

A refinement of this testing technique would be to place one of these error measurement systems on each machine axis. Then a multi-axis contouring program could be run under tape control while monitoring the dynamic slide error. These data could then be used to obtain qualitative figures of potential contouring accuracy. With this application, the NC data tape could be modified to reduce the machining error. In addition, the error monitor could easily be adapted to be the position feedback device for a computer-controlled machine tool.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to T. W. Davidson for his efforts in establishing a basic design concept; to W. L. Goodwin for his help in determining the output characteristics of the pulse output laser interferometer, and to H. A. Tunnell and his machine checkout group for their cooperation in testing and evaluating the system.

APPENDIX

SYSTEM DRAWINGS

Figure A-1. NUMERICALLY CONTROLLED ERROR MONITOR SYSTEM. (Miscellaneous Diagrams)

Figure A-2. NUMERICALLY CONTROLLED ERROR MONITOR SYSTEM. (Logic)

Y-1845

DISTRIBUTION**Atomic Energy Commission-ORO**

Hickman, H. D.
Zachry, D. S., Jr

Oak Ridge Gaseous Diffusion Plant

Wilcox, W. J., Jr
Winkel, R. A.

Oak Ridge Y-12 Plant

Alvey, H. E.
Bernander, N. K.
Briscoe, O. W.
Burditt, R. B.
Burkhardt, J. H., Jr (12)
Burkhart, L. E.
Davidson, T. W.
Denny, A. (2)
Ellingson, R. D.
Fouk, D. L.
Goodwin, W. L.
Hemphill, L. F.
Jackson, V. C.
Jones, F. W.
Kahl, K. G.
Keith, Alvin
Kite, H. T.
Lay, C. M. (4)
Lee, W. W.
Mason, D. L.
McLendon, J. D.
Mitchel, G. W.
Oliphant, G. W.
Smith, H. F.
Smith, J. H.
Smith, R. D.
Speller, B. W.

Stephens, W. E.
Stoner, H. H.
Trotter, T. C.
Tunnell, H. A.
Weathersby, W. E.
Webber, T. R.
Wright, C. C.
Yaggi, W. J.
Y-12 Central Files (5)
Y-12 Central Files (master copy)
Y-12 Central Files (route)
Y-12 Central Files (Y-12RC)

Paducah Gaseous Diffusion Plant

Levin, R. W.

In addition, this report is distributed in accordance with the category UC-37, **Instruments**, as given in the *USAEC Standard Distribution Lists for Unclassified Scientific and Technical Reports*, TID-4500.