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Engineering and
Equipment

MASTER

SPINDLE GROWTH COMPENSATION SYSTEM FOR
NUMERICALLY CONTROLLED LATHES

H. P. Prewett
C. H. Thompson

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

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CARBIDE**

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Nuclear Division

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ABSTRACT

An automatic spindle-growth compensation system has been developed and installed on a numerically controlled lathe, equipped with a machine tool control unit, at the Oak Ridge Y-12 Plant. An air gage was selected to continually monitor spindle growth and supply a proportional electrical output signal through interface electronics to the lathe control unit.

Test results demonstrated that: (1) uncompensated spindle growth will have a direct effect on the length dimensions of a workpiece, and (2) the system will maintain the carriage in its programmed position relative to the spindle within ± 100 microinches over a six-mil range of spindle growth.

CONTENTS

SUMMARY	5
INTRODUCTION	6
DEVELOPING THE COMPENSATION SYSTEM	7
Experimental Program	7
Conclusions and Recommendations	12
ACKNOWLEDGEMENTS	13
APPENDIX	15
Spindle Growth Compensator Installation and Operation Manual	15

SUMMARY

Engineers at the Oak Ridge Y-12 Plant^(a) developed an automatic spindle growth compensation system and installed it on a LeBlond numerically controlled lathe with a GE Mark Century control unit. A Sheffield air gage was selected to continuously monitor spindle growth and supply a proportional electrical output signal through interface electronics to the numerically controlled lathe control unit. The control unit would then offset the lathe carriage from its programmed position, thereby compensating for spindle growth.

Test results demonstrated that: (1) uncompensated spindle growth will have a direct effect on the length dimensions of a workpiece; (2) the system will maintain the carriage in its programmed position relative to the spindle within ± 100 microinches over a six-mil range of spindle growth.

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

INTRODUCTION

Personnel at the Y-12 Plant have long sought to obtain the best possible accuracy and precision in machine tools.

For many years, spindle growth on numerically controlled lathes has been recognized as a machine error which limits the accuracy and repeatability of the machine tool. In fact, spindle growth has a direct influence on workpiece length.

In the interest of numerically controlled lathe improvement, a program was initiated to develop a system that would eliminate or minimize the effects of spindle growth on workpiece dimensions.

It was proposed to continuously monitor the spindle growth using a displacement sensing device with a linear electrical output signal. The signal could then be modified and used in the numerically controlled machine tool control unit to offset the programmed carriage position, thereby continuously compensating for spindle growth.

It was hoped that the lathe carriage would maintain its programmed relation with the spindle within the limit of the positioning capability of the machine.

DEVELOPING THE COMPENSATION SYSTEM

EXPERIMENTAL PROGRAM

A LeBlond 3220 numerically controlled lathe with a GE Mark Century control unit^(b) was acquired for use in developing an automatic spindle growth compensation system.

Test evaluations were made to determine the best type of noncontact displacement measuring device for measuring spindle growth. A Wayne-Kerr gage and a Dynagage (both capacitance-type gages), and a Sheffield air gage were evaluated. Effects of range, linearity, drift, response, and environmental conditions were primary considerations.

Of the parameters measured, range and linearity differences among the three devices were relatively insignificant for the application. Both the Dynagage and the Wayne-Kerr gage possessed very fast responses, but were restricted because of the environmental conditions of coolant, dust, or chips during machining operations.

The Sheffield air gage appeared to be the most suitable device for the following reasons: (1) the output signal drift was within the desired limit; (2) filters were not required since its low response did not detect axial runout of the reference surface; (3) coolant, dust, or chips were kept from between the jet and reference surface by the air flow, thereby giving a continuously accurate measurement.

To minimize the setup time when using the Sheffield air-gage system, it was necessary to use a permanently mounted adapter plate to which part fixtures could be attached. The adapter was attached to the lathe, and the back of the plate was ground flat to within ± 100 microinches to provide a reference surface for the air nozzle.

Figure 1 shows the relative location of the air nozzle on the LeBlond lathe. Mounting of the air jet was made in a way that would minimize any movement of the nozzle in relation to the bed of the lathe.

Two systems were investigated for injecting the signal from the Sheffield air gage into the GE Mark Century control unit. One system applied the error compensation signal to the control unit in digital form at the command phase counter, the second system inserted the compensation signal at the summing point of an operational amplifier located in the existing command section of the Mark Century servo control loop. The second system was selected due to its simplicity, lower cost, and better control.

Figure 2 presents a block diagram of the system chosen for spindle growth compensation.

(b) General Electric Numerical Contouring Control, GEK-284, Control Serial 84762, Model 3S7512CC152D1.

128700

Figure 1. AIR NOZZLE INSTALLED ON THE NUMERICALLY CONTROLLED LATHE.

Figure 2. SIMPLIFIED MARK CENTURY SINGLE-AXIS CONTROL UNIT WITH SPINDLE-GROWTH COMPENSATION.

The signal output from the Sheffield air-gage linear variable differential transformer (LVDT) is amplified and demodulated by a Sheffield Accutron mounted on two circuit boards. The output of the Accutron is a DC voltage level that is proportional to the distance between the air-jet nozzle and the reference surface (adapter plate). The system was calibrated to provide a voltage output of 200mv per 100-microinch change in gap between the reference surface and the nozzle. A zero-volt output is set by a centering potentiometer with the aid of a galvanometer.

The output of the Accutron is filtered, inverted, and amplified by an operational amplifier. The amplifier output is fed into a one-megohm trimpot that supplies current to the machine control summing point. The "Y" position (carriage position) error signal is summed with the spindle growth compensation signal to provide continual automatic tool offset as dictated by the movement of the spindle.

The total system was calibrated so that the carriage maintained its programmed position with the spindle within ± 100 microinches over a six-mil range of spindle growth.

Two test parts were cut to show the maximal effects of spindle growth with and without the spindle growth compensation system. Figure 3 shows the uncompensated part; Figure 4 shows the compensated part. Cutting procedures for both parts were as follows: The parts were cut across the face in a series of 0.500-inch bands using the cross slide only. After each band was cut, the tool was left in place and the spindle operated for ten minutes, allowing the spindle to grow. Another band was then cut. In this study, the spindle was run at 500 rpm between Bands 1, 2, and 3 and at 1,300 rpm between Bands 3, 4, and 5. Small cuts and a micarta vacuum chuck between the part

Figure 3. UNCOMPENSATED PART FACE. (All Measurements are from the Zero Reference Plane)

Figure 4. COMPENSATED PART FACE. (All Measurements are from the Reference Plane)

and the adapter kept temperature generation in the part at a minimum; no coolant was used.

Measurements from a zero reference plane at the outer edge of Band 1 revealed the errors in the finished parts. It was particularly interesting to note that the error in the uncompensated part (Figure 3) followed the spindle growth chart recording during the test within ± 150 microinches. By checking the inspection results of the uncompensated part (Figure 3) and the compensated part (Figure 4), it is easily noted that the maximum error was reduced from -5.9 to $+0.3$ mils with the spindle growth compensation system.

Both parts were cut with the most extreme conditions of spindle growth. During actual production of parts on this machine, only a portion of this spindle growth will be generated. Because of the very small, slow incremental movements ($100 \mu\text{in}$) that were made with the carriage from a static position, striction or static friction made it impossible for the machine to cut the compensated test part so that it would indicate the ultimate capability of the system.

With the carriage moving in a automatic cycle, spindle growth was compensated for within ± 100 microinches over a spindle-growth range of six mils. (Range of growth was limited due to the linearity of the air gage system.) This conclusion was proven by the following test: An LVDT was placed on the Y slide and set against the carriage so that the Accutron amplifier read zero. The carriage was then commanded to move four inches toward the lathe headstock and then back to the LVDT at a low feed rate in the semiautomatic mode. The Accutron reading was reset to zero to eliminate backlash. According to the Accutron, using the same procedure, the carriage returned to the zero point within ± 100 microinches. For discussion purposes, call the zero point, Point A, and the point nearer the lathe headstock, Point B. A Go-Devil micrometer was used to simulate spindle growth. The spindle growth compensator was then connected to the machine control circuit, as shown in Figure 2. During movement from Point A to Point B, a spindle growth of one mil was simulated. An additional one-mil spindle growth was simulated during the return movement from Point B to Point A. That the carriage returned to a position equal to Point A plus two mils within ± 100 microinches was indicated by the Accutron.

During the next test cycle, movement of the spindle in the opposite direction was simulated. An increment of spindle movement of one mil was extracted from the system during movement from Point A to Point B and then again during the return movement from Point B to Point A. The carriage stopped at Point A within ± 100 microinches. Various other amounts of spindle growth were simulated and the results mainly indicated two things: (1) during slide movement, the carriage was offset in relation to spindle growth within ± 100 microinches; (2) lead screw backlash did not affect the system.

Drift tests indicated that the system was stable. Maximum deviations of ± 40 microinches about a zero point were realized. Continued drift was negligible.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be stated:

1. An air gage is suitable for detecting machine-tool spindle growth due to its inherent small signal drift and low response.
2. Numerically controlled machine-tool errors can be compensated for by inserting the error compensation signal into the command section of the tape control unit servo control loop.
3. Spindle growth directly affects workpiece length.
4. Workpiece length error, due to spindle growth, can be reduced to within the positioning capability of the machine tool.

It is recommended that spindle growth compensation systems be installed on numerically controlled machine tools where spindle growth relates to the out-of-tolerance condition of machined parts.

ACKNOWLEDGEMENTS

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APPENDIX

SPINDLE GROWTH COMPENSATOR INSTALLATION AND OPERATION MANUAL

Section I

General Information

1.1 Description

1.2 Purpose and Capability

The spindle growth compensator is a pneumatic and electrical device for detecting and compensating for machine tool spindle growth. The device will compensate for spindle growth within ± 100 microinches over a growth range of six mils.

1.3 Principles of Operation

The spindle growth compensator detects spindle growth by monitoring the gap between the stationary air jet nozzle and the reference surface permanently mounted on the spindle (See Figure A-1, Section VI). The back pressure from the air nozzle is converted to an electrical signal by a Sheffield pneumatic-to-electrical transducer (See Figure A-2, Section VI). This signal is then amplified, demodulated, and filtered. The resulting DC level, proportional to the spindle growth, is then summed with the machine control unit commands. This step is accomplished at the summing point of the appropriate axis servo loop operational amplifier. The results of this summing action commands the appropriate slide to be offset continually from its programmed position according to the movement of the spindle, therefore compensating for spindle growth (See Figure A-3, Section VI).

Section II

Installation

2.1 Introduction

This section supplies information for installing and calibrating the spindle growth compensator.

2.2 Component Installation

2.3 The air jet nozzle should be mounted at a location that will meet the following requirements (for an example, see Figure A-1):

2.3a A three-mil gap between the end of the nozzle and the reference surface (attached to spindle) with the spindle at ambient temperature.

2.3b Low conduction of heat from the machine through the nozzle support.

2.3c Minimum movement of the nozzle due to movement of the slides.

2.4 Copper tubing is used between the machine tool and the logic control unit. Flexible tubing is used from the copper tubing to the air gage and to the air jet nozzle. Copper tubing is also used for piping instrument air to the air gage.

2.5 The Sheffield air gage should be mounted in the machine logic control unit cabinet at a location that is readily accessible for maintenance purposes. The control unit cabinet offers a temperature variation within $\pm 1^\circ \text{F}$. The air gage may be located external to the control unit provided the temperature does not vary more than $\pm 2^\circ \text{F}$. Shielded electrical cable, grounded to the machine control unit ground, is used between the air gage and the Sheffield Accutron.

2.6 The Sheffield circuit board mounted demodulator and amplifier should be mounted in the machine tool logic control cabinet, preferably in the logic card rack if space is available. If mounted external to the control unit cabinet, a (-) 15 vdc regulated power supply will be required. The compensator requires an Accutron with an extended range. To extend the range of the Accutron, replace the 50 kohm range trimpot with a 100 kohm trimpot. A zener diode is used with the machine control regulated voltage supply to supply (-) 15 vdc to the Accutron. The range, centering, balance, and null trimpots should be readily accessible for calibration adjustments by maintenance personnel. The centering resistance pot and the centering galvanometer should be mounted on the face of the machine logic control unit. The output of the Accutron is transmitted to the spindle growth compensator current source (SGCCS) circuit board by a shielded single conductor cable.

2.7 The spindle growth compensator current source (SGCCS) is mounted on a circuit board that will fit into the existing machine logic card rack. All components are to be mounted and wired as per Figure A-3. Mount a BNC chassis connector on the logic card rack, connect it to the OA output for monitoring spindle growth.

The output of the SGCCS is transmitted to the spindle compensator relay (RSC) by a shielded cable.

- 2.8 The spindle compensator relay (RSC) is mounted in the machine logic control cabinet. The RSC relay is controlled by the machine mode of operation and punched tape. The RSC relay will control the insertion and rejection of the compensation signal from the summing point of the operational amplifier. An indicating light, mounted on the machine tool control console, will also be controlled by the RSC relay to indicate the insertion of the compensation signal. Logic gates, flip flops, and a relay puller are used, as shown in Figure A-3. The compensation signal cannot be in the circuit during the tool set mode. The signal can only be inserted by an M function from tape or by manual data read in. The signal, from the RSC relay, is transmitted through shielded cable to the summing point.
- 2.9 The following calibration procedures should be followed in the order as listed.
- 2.10 The Sheffield air gage is calibrated as follows:
 - 2.10a The toggle valve, located on the front of the transducer panel, must be open.
 - 2.10b Set the pressure regulator to approximately 17 psig.
 - 2.10c Obtain magnification reading on the nozzle-pressure indicator (PI) by using a Go-Devil micrometer. The reading on the nozzle PI should be zero at a three-mil gap and +2 at a five-mil gap.
 - 2.10d If the magnification readings are incorrect, correct as follows:
 1. If the magnification is below the correct value listed in Step 2.10c, adjust the pressure regulator to increase the air pressure and adjust the variable orifice clockwise to obtain the correct reading.
 2. If the magnification readings are higher than the correct value, adjust the pressure regulator to decrease the air pressure and turn the variable orifice counterclockwise to obtain the correct reading.
 - 2.10e Repeat the check with the Go Devil at least three times to obtain a good calibration.
- 2.11 The Sheffield Accutron and the SGCCS operational amplifier (OA) are calibrated as follows:
 - 2.11a Connect a vacuum tube millivoltmeter to the output of the SGCCS OA.

- 2.11b Use standard procedures for trimming the OA for a minimum DC offset.
- 2.11c With a three-mil gap between the air jet nozzle and a reference surface (use a Go-Devil micrometer), set the output of the OA to zero volts with the centering resistance pot.
- 2.11d With a seven-mil gap, adjust the OA voltage output to eight volts with the range trimpot.
- 2.11e Set the OA output voltage at a maximum with the null trimpot.
- 2.11f Readjust the range trimpot for an OA output voltage of eight volts.
- 2.11g Repeat Step 2.11c.
- 2.11h Return to a seven-mil gap and check the OA output voltage. If output voltage is not at eight volts, set to eight volts with the range trimpot. OA gain should be at about 1X.
- 2.11i Repeat Steps 2.11c and 2.11h using the balance trimpot for linearity adjustments.
- 2.11j Continue Step 2.11i until the proper output voltage is repeated without further adjustment of the centering, balance, and range trimpot.
- 2.11k Check linearity every 0.5 mil starting at a gap of 2.5 mils and continuing to a gap of 8.5 mils. The voltage output of the OA should be linear to within ± 200 mv over this range. Continued adjustment of the Accutron and the OA is made to insure linearity.

Important Note: The Accutron and OA do not have to be adjusted for an output signal of 200 mv per 0.1-mil gap change. Other signals per unit gap change may be selected provided that linearity is held to within ± 0.1 mil. Adjustment of the SGCCS output resistor will compensate for other signals.

2.12 The SGCCS output trimpot is adjusted in the following manner:

- 2.12a Disconnect the filtered output of the machine control operational amplifier being used to sum the machine error command with the spindle growth compensator signal.
- 2.12b Connect a VTVM to the servo loop OA.
- 2.12c Record the output of the OA.

- 2.12d Manually command the machine slide to move 3 mils in a direction opposite to the spindle growth.
- 2.12e Set the gap between the air jet nozzle and reference plate with a micrometer to six mils.
- 2.12f Apply the spindle growth compensator signal to the machine control OA summing point. Adjust the OA output voltage to zero using the SGCCS output trimpot.
- 2.12g Reconnect the output of the machine control OA to the servo loop.
- 2.13 An additional calibration check of the spindle growth compensator can be made using the following procedure:
 - 2.13a Use a portable Accutron and an LVDT to record the slide movement. Take out the backlash.
 - 2.13b Put the air jet nozzle in a Go-Devil micrometer.
 - 2.13c Set gaps at 3, 4, 5, 6, 7, and 8 mils. Insert the compensation signal at each gap. The slide should move 0, 1, 2, 3, 4, and 5 mils, respectively, ± 0.1 mil.

Section III

Operation

- 3.1 Introduction
- 3.2 The following operating information is supplied as a general guideline to insure effective use of the spindle growth compensator.
- 3.3 Operating controls consist of a centering resistance potentiometer, a centering galvanometer, a spindle growth compensator in/out switch, and an in/out indicator light.
- 3.4 Tape programming controls the insertion and extraction of the spindle growth compensation signal. The signal is controlled by an MXX function. The programmer must insert the MXX function, to turn on the compensator, between the zero starting point and the first point of cut while the Y slide is in motion. If not using the automatic tool setter, the programmer must insert the proper MXX function to turn on the compensator before obtaining a zero position from a part or fixture. The programmer also may turn the signal off with a different MXX function. This MXX function will only be programmed in unusual cases.

- 3.5 Recognition of an automatic tool set mode, an MXX function, and the automatic mode controls the insertion and extraction of the spindle growth compensation signal. When the machine tool goes into the automatic tool set mode, the spindle growth compensation signal is turned off. To turn the compensation signal back on, an MXX function must be read into the control unit and the machine must be in the automatic mode. A switch mounted on the machine logic control card rack will allow the compensation signal to be programmed or manually inserted into the machine control unit in the "in" position. In the "out" position, the compensation signal cannot be manually inserted or programmed into the machine.
- 3.6 Operating procedures for using the spindle growth compensator are divided into two categories:
- 3.7 When using an automatic tool setter, the spindle growth compensator indicator light, located on the operator's console, should function as follows:
- 3.7a The light should be off during the tool set mode.
- 3.7b The light should be on during the actual cutting of the part.
- 3.7c The light should be on when the operator determines any tool offset in relation to the part. Note: All incremental feeds must be made with the mode selector switch in the automatic position.
- 3.8 When not using an automatic tool setter, the spindle growth compensator indicator light, located on the operator's console, should function as follows:
- 3.8a The light should be on when setting off the part or the fixture. Have the compensator and program checked if the light is not on.
- 3.8b The light should be on during the cutting cycle.
- 3.9 The following operating precautions should be used:
- 3.9a Maintain a clean adapter reference surface. Coolant on the reference surface should not be a problem.
- 3.9b Check the spindle growth compensator light for proper operation as noted in Sections 3.7 and 3.8.
- 3.9c When using the spindle growth compensator, the spindle compensation switch, mounted in the logic control card rack, must be in the "in" position.

Section IV

Maintenance

4.1 Preventive Maintenance

4.2 General

For the spindle growth compensator to give accurate, trouble-free operation, periodic performance and visual checks must be maintained.

4.3 The following performance checks must be made to insure proper operation of the spindle growth compensator.

4.3a Inspection result trends of parts cut, while using the spindle growth compensator, should be reviewed. An unexplainable change in the trend may indicate a faulty compensator.

4.3b When the machine tool spindle is at ambient temperature, the centering galvanometer should be within ± 50 microamperes of zero with the machine control on.

4.4 An Instrument maintenance check should be performed on the Sheffield air gage at intervals not to exceed one month. The air gage should be visually inspected. A check of the air gage calibration can be made using the procedure outlined in Paragraphs 2.10a and 2.10c. If the calibration is incorrect, use the entire procedure given in Subsection 2.10. If the gage cannot be calibrated, replace it with a spare gage.

4.5 Electrical maintenance should be performed on the compensator following the instrument maintenance check. Follow the procedure given in Subsection 2.13. If the movement of the slide does not meet the specification in Paragraph 2.13c, recalibrate the compensator using the procedure outlined in Subsections 2.11 and 2.12. Circuit diagrams are listed in Section VI for trouble shooting the compensator.

Section V

Replacement Parts

5.1 This section contains a parts list and ordering information for the spindle growth compensator.

5.2 Replacement parts for the compensator are listed in the Appendix.

Section VI

Circuit Diagrams and Component Identification

6.1 This section presents mechanical drawings, flow diagrams, and circuit diagrams.

6.2 Figure A-1 is a mechanical drawing showing the general location of the air nozzle in relation to the adapter plate on a numerically controlled lathe.

Figure A-1. SPINDLE-GROWTH SENSING ELEMENT MOUNT.

6.3 Figure A-2 is a flow diagram of the Sheffield air gage.

6.4 Figure A-3 is a circuit/block diagram of the spindle growth compensator.

Figure A-2. SHEFFIELD AIR GAGE.

Figure A-3. SPINDLE GROWTH COMPENSATION.

Section VII

Replacement Parts List

<u>Item Number</u>	<u>Component</u>	<u>Number of Parts Required</u>	<u>Manufacturer's Part Number</u>	<u>UCC-ND Stores Number</u>
1	Sheffield Air Gage with Nozzle(a)	Regulated Pressure Indicator (1)		Use UCC Register Number M9953
		Pressure Control Valve (1)		
		Variable Orifice (1)		
		Nozzle Pressure Indicator (1)		
		Toggle Valve (1)		
		Pneumatic to Electronic Transducer (1)		
		OC Nozzle Connector (1)		
		Air Supply Connector (1)		
		Air Nozzle Tubing, as Required		
		Cable, as Required		
2	Tubing (1/4" ID)	Copper Tubing, as Required		
		Flexible Tubing, as Required		
3	Tubing (3/16" ID)	Flexible Tubing, as Required		
4	Sheffield Accutron	Module Assembly, Accutron (1)	C50518632	06-511-4300

(a) Figure A-3 shows logic gates, flip flops, relay pullers, relays, and indicating lights as required for installation on a GE Mark Century control unit. When installed on a Bendix control unit, use Bendix logic as required for the same effect.

Replacement Parts List (continued)

<u>Item Number</u>	<u>Component</u>	<u>Number of Parts Required</u>	<u>Manufacturer's Part Number</u>	<u>UCC-ND Stores Number</u>
		Trimpot (100 k, 1/2 w) (1)	Bourns 200L-2M	06-511-4300
		Zener Diode*(b) (1)	1N3024B	06-995-7098
		Resistor (43 Ω *, 1 w) (1)	Allen-Bradley Type GB	06-932-1968
		Meter (50-0-50 microamps) (1)	Weston 306-56011	06-050-1825
		Potentiometer (100 ohms) (1)	Beckman AR100L.25	06-930-2844
		Dial-Turns Counting (1)	Beckman Model 2606	06-881-4162
5	SGCCS	Operational Amplifier (1)	Philbrick PP65AU	
		Resistor (750 kohm, 1/2 w, 1%) (1)		06-932-0227
		Trimpot (1 megohm, 1/4 w) (1)	Bourns 235P	
		Trimpot (50 kohm, 1 1/2 w) (1)	Helitrim Series 53	06-930-8218
		270 Resistor* (1 w) (1)		06-932-2063
		Zener Diode* (1)	1N3022B	06-995-7094
		Capacitor (0.15 mfd) (1)	Sprague 192P15452	06-808-8170
6	Connector	BNC Connector (UG625/u) (1)	Dage Electric 100-081-1	06-841-6300
7	Switch	Rotary Switch (1)	Centralab 1403	06-970-1704

(b) Parts listed with an asterisk are required only when the compensator is installed on a GE Mark Century control unit.