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AEC RESEARCH AND DEVELOPMENT REPORT

1030
Y-1692
Engineering and
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MASTER

COMPUTER-ASSISTED, ADAPTIVELY CONTROLLED
MACHINE TOOL SYSTEMS

T. L. Williams

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

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

**UNION
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Date Issued: October 3, 1969

Document Y-1692

TID-4500

UNION CARBIDE CORPORATION
Nuclear Division

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Contract W-7405-eng-26
With the US Atomic Energy Commission

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ABSTRACT

In anticipation of the development of a computer-augmented, adaptively controlled, multiaxis machine tool, a literature search was made to determine the availability of hardware that might be used in such a system and to accumulate pertinent information derived from research directed toward such a system.

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SUMMARY

A literature search was made in an effort to accumulate pertinent information on computer-controlled machine tool systems and real-time adaptive control (AC) techniques. The findings are to be used as preparatory material for the development of a computer-augmented, adaptively controlled, multi-axis machine tool. Desirable information included: (1) available systems that might be used directly or modified to suit the existing needs; (2) benefits that might be derived from an AC system; (3) machining variables and their effects; (4) AC techniques.

The findings of this investigation indicate that many advantages can be derived from the application of adaptive control to machine tool systems. It has been concluded that the time is right for the machining industry to enter the new era of computer-augmented adaptive control of machine tools.

INTRODUCTION

In anticipation of a development program on computerized adaptively controlled (AC) machine tools, a study was made of the present state of the art. This report is designed to summarize what industry has done toward such a system and attempts to relate the results to the particular machining problems encountered at the Oak Ridge Y-12 Plant.^(a) Since all or part of this information is known by many of the Plant personnel, the purpose of this report is to assemble this information so that any future development projects will be undertaken with a basic knowledge of the difficulties involved and with some concept of what should be included in the final system.

Since the advent of numerically controlled machine tools in the early 1950's, considerable progress has been made in their application. Numerical control units are now being used on machines that are used for: milling, welding, grinding, turning, filament winding, drilling, tapping, boring, and punching. These controllers have made possible the manufacture of intricately precise parts that, beforehand, were impracticable if not impossible to produce.

However, even with all its assets, the numerically controlled (NC) machine has some drawbacks. The high-speed tape reader and analog servo system present electronic difficulties that introduce excessive downtime. There are also problems with the mechanical aspects of the servo system. Gear boxes between the lead screws and feedback resolvers introduce backlash, the machine slides are not always where the feedback resolvers indicate they should be (due to such factors as temperature changes and lead screw inaccuracies), and there is always a lag (due to the mass being moved) between the NC commands and the response of the servo system.

The closer tolerances, demanded by present-day machining specifications, require that some type of compensation be introduced to eliminate significant portions of these errors. Also, increasing interest in better surface finishes and part integrity is stimulating research in AC techniques to include these parameters in the finished part. Although much research has been and is being done, the contribution of each particular machining variable to the quality of the finished product is not fully understood. Research in AC techniques has been hindered because of the inflexibility of the conventional

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

NC unit. Changing an experiment usually requires extensive modifications to the control system's electronics. A control system incorporating software (eg, a computer) would provide much of the flexibility needed to fully investigate these variables.

In the past, industry's most pressing problem has been to turn out the most acceptable parts at the smallest production cost. AC research has been influenced by this attitude. It is obvious here at Y-12 that the way to decrease production costs is to minimize part rejection and the failure rate. Industry, particularly that of civilian aircraft, is turning toward this philosophy. Here, a failure can result in a multiple loss of lives. With the advent of the supersonic transport and large-capacity (500 passengers) aircraft, a failure could bring about a national tragedy. This new challenge has initiated research projects with new attitudes toward part production. More attention is being paid to what actually is happening to the workpiece as the part is being machined. Generally, if a part is made at a higher precision level than "just acceptable", it will last longer with lower failure rates. As soon as this attitude permeates industry, a more complete effort on AC research projects will be noted.

ADAPTIVE CONTROL

LITERATURE SEARCH

Introduction

There are probably as many variations in the definition of "adaptive control" as there are experts in the field of machine tool control. Webster's Dictionary states that "to adapt is to modify to meet new conditions", and "a control is a mechanism used to regulate or guide the operation of a machine". As a result of combining these two definitions, AC may be defined as the modification of a mechanism used to guide the operation of a machine to meet new conditions. Kahl⁽¹⁾ and Billig⁽²⁾ state that an adaptive system is one which is provided with a means for continuously monitoring its own performance in relation to a specified index-of-performance or optimum condition and with a means for modifying its own control parameters by closed-loop action in order to approach this optimum condition. This latter definition is a general type of statement and is subject to interpretation. Monitoring and modification could be either real time or otherwise. The optimum condition mentioned is determined by the type of system involved and is subject to engineering and economic judgements. In a report submitted by Center,⁽³⁾ the primary motivation for the application of AC to a milling process at Bendix was the urgent need for improved productivity and efficiency, especially for NC machines which are costly to operate. There are some manufacturers whose objective is the production of ultraprecision parts with respect to surface finish and contour. It is obvious that the cost of this type manufacturing process can be minimized by reducing the rejection rate. With this viewpoint in mind, any AC criteria developed for use at Y-12 would need these features as the primary conditions.

Most AC systems that are available today monitor torque and tool-tip temperature or tool deflection as feedback information to control both the feed-rate and spindle speed for achieving maximum production, minimum cost, or some balance between the two. Constraints are placed on other machining parameters to assure part precision and adequate surface finish. Recent development projects are looking deeper into some of these constrained parameters as a means of adaptively controlling machines to achieve these objectives.

During the next few years, a concerted effort will be extended toward applying computer-controlled machine tools and real-time AC to production processes. With this in mind, a literature search was made to investigate the AC systems

that are now available and the development work that has been done on these systems.

Development of Adaptive Control Techniques by Bendix

Description - One of the first efforts toward real-time adaptive control of machining processes was applied by the Bendix Corporation.⁽³⁾ Their system measures on-line torque, temperature, and vibration data for use as feedback information for adjusting feed and speed values to obtain and maintain optimum cutting conditions (minimizing cost, maximizing production, or some combination of the two). The prototype system that was developed consists of a milling machine, a continuous-path NC system, and a special-purpose device called the adaptive controller which is a hybrid analog-digital computer. The computer performs an on-line evaluation of metal-cutting performance based on the values of the sensed parameters (spindle torque, tool vibration, and tool-tip temperature) and predetermined performance criteria. It then generates feed and spindle-speed correction commands in an attempt to optimize performance with limits on certain constraints placed upon the system. These constraints assure that an acceptable part is being produced. This process of performance evaluation and feed-speed corrections takes place continuously as metal is being removed and thereby enables the controller to adapt to such changing metal-cutting conditions as: tool dulling, variations in workpiece hardness, and variations in cutter load.

Discussion - The Bendix analog-digital computer consists of electronic circuitry that is hard wired to perform the required calculations. This type of system is inflexible in that any changes in the experimental procedure require that the computer be redesigned.

This type of optimizing is of questionable value to the production processes at Y-12. It is of prime importance to keep production costs at a minimum, but the means for attaining this goal differ. If the number of rejected parts can be controlled through better control of surface finish and better machine-cutting accuracy, production costs will take care of themselves.

The applicability of the optimizing formula used in this system is questionable. This problem is due to the inability to predict or measure the tool wear rate which leads to an error when determining the cost of the cutting tool.⁽⁴⁾

Software Approach to Adaptive Control - Bendix

Description - Bendix is developing a computer-augmented NC system.⁽⁵⁾ A small, general-purpose computer with a memory capacity of 4,096 twelve-bit words is employed to perform the following functions:

1. Temporarily store control data read in from the high-speed tape reader.
2. Service the machine control unit whenever it needs a block of data.
3. Modify the stored control data in response to information obtained from sensors on the machine tool.

The operating program, written by Bendix, is a compact software package that services the machine control unit and associated devices on the machine console. Ten blocks of control data are stored in the computer in such a way as to minimize the time spent in housekeeping. These blocks are available to an AC program which can modify upcoming controller data based on information sensed at the machine tool.

Discussion - Optimization techniques to be used in this software system are not presented. It is probably safe to assume that these will be the same as those used in the hardware system.⁽³⁾

This design approach is similar to that advocated by some Y-12 personnel. These people recommend that the NC unit be used as it is with the computer performing such mathematical functions as: prediction of tool-wear-rate compensation factors, workpiece expansion corrections, generation of position data from part equations or curve-fitting techniques, and any other corrections that require mathematical calculations.⁽⁶⁾

It should be pointed out that the use of the small 4K twelve-bit word computer will probably force the use of a standard NC unit if AC is incorporated into the system. The use of a larger computer (18-bit word with 4 - 8K memory) as the control device gives a more powerful tool that can be used for part generation and AC as well as performing most if not all of the NC unit's function.

Cincinnati Milling Acramizer

Description - This AC system monitors spindle deflection and torque to adjust the feeds and speeds of a three-axis NC contouring mill so that material is removed at the lowest possible cost. The deflection signal is also compared with the part's tolerance to insure accuracy. Through metal-cutting research, the Physical Research Department of the Cincinnati Milling Machine Company has discovered a feedback quantity composed of cutter torque and deflection with a relative response to process variables of the same order and magnitude as its respective influence on cutting speed for constant tool life.^(7,8) Having this feedback quantity enabled them to construct an AC system. The

controller is an integral part of the NC system. Cutter deflection sensed at the spindle nose and cutter torque sensed in the spindle are continuously measured by electrical transducers. Sensor signals are received by the adaptive controller which computes the feedback quantity and determines the optimum speed and table rate. There are also constraints which the controller obeys. It compares the cutter deflection with a limiting value to prevent tool destruction and to insure correct part dimensions. The controller also compares deflection and torque signals with near-zero values to sense a tool path through air. When this action occurs, feedrates are increased to achieve efficient operation. It also receives a signal proportional to the horsepower consumed at the motor, which is compared with the horsepower capacity of the machine. Based on these computations, corresponding table rate changes are instantaneously commanded by the adaptive controller.

Bunker Ramo System 70

Description - The system consists of a 16-bit-word, 8K memory computer with a 500K word disc unit for storage of part description programs, therefore eliminating the tape reader. The computer is capable of simultaneously controlling ten machine tools.⁽⁹⁾ The control unit at the machine has been simplified through the use of the computer software. Conventional NC units contain small, special-purpose computers that read, convert, and interpolate tape data for machining slopes and arcs. In addition, these units designate the end point of each move made by the tool as it contours the material. With computer control, all of the electronics not needed for direct control of the machine slides and other functions are located in the controlled environment of a data processing room. Signals travel from the computer to individual machines on shielded cables that can be nearly a mile long. Because of the absence of the conventional tape reader and special-purpose computer, the System 70 control is much smaller than a standard NC unit. Because of its simplicity, it is inherently more reliable.

Discussion - When driving the maximum number of machines, most of the computer time is taken. A system such as this could be modified for AC. This change would most likely reduce the number of machine tools that can be controlled by a single system. AC techniques, especially those that require mathematical computations, require a significant amount of computer attention.

Sundstrand's Omnicontrol System

Description - Several models of the IBM 360 Series computers have been mated to multiaxis machine tools.⁽¹⁰⁾ Up to 255 five-axis machines can be controlled with one computer (IBM 360 50 with 512K of active memory) without

disturbing regular data processing operations. Even the smaller computer (IBM 360 30 with 65K of active memory) can control up to 16 five-axis machine tools in addition to its regular work.⁽¹¹⁾ This system consists of a computer, two disc files for storing part programs, a programming console unit which contains machine control logic located at each machine tool on the production floor, an omnicontrol master unit which establishes contact and directs the flow of data between the computer and console, and a cathode-ray tube/keyboard combination for communication with the computer. A cable up to 2,500 feet long links each machine logic unit with its control unit in the data processing room.

The computer is used for programming as well as machine control. An unusual feature of the omnicontrol system is that programmers can converse with the computer via typewriter or CRT with typewriter keyboard. Working at the machine site, the programmer can make program changes or even develop a program on the spot. His input to the computer is translated into point-to-point machine control commands and stored on a disc.

Elimination of an NC system and tape reader for each machine reduces the cost of control for multimachine installations.⁽¹¹⁾ The initial investment is less than for conventional NC when three or more machines are computer controlled.

Discussion - The statement about savings assumes that the appropriate computer is already on hand and available for this type of operation. If a new computer has to be acquired, the cost-justification arguments are invalid.

Personal interviews with Sundstrand personnel reveal that AC development is being pursued, but it was suggested that real advancements in these techniques awaits the development of appropriate sensors for monitoring the machine variables. This particular problem will be covered in a later section of this report.

Machine Control Company's Computer Numerical Control

Description - The Machine Control Company (MCC) has learned to successfully time-share and program a small (4K core) computer to work efficiently and economically as an NC director.⁽¹²⁾ A total of 6 two-axis contouring machines can be controlled simultaneously and independently for manufacturing six different part shapes. This step is accomplished through the use of a low-cost computer programmed to execute NC mathematical interpolations while simultaneously performing such machine tool housekeeping chores as: reading part tapes, observing interrupts, and enacting canned cycles. In short,

MCC has soft wired a computer to perform as an NC director. MCC's COMPUTA-PATH System is not just an interface between an NC unit and a computer that is replacing a tape reader, but the small, general-purpose computer is the NC. In some simple applications, portions of the computer's 4K core memory can be reserved for part program data.

Discussion - This system is similar to any that might be acquired at Y-12. It would be advantageous to take a system such as this and adapt it to include cubic curve-fitting techniques for free-form parts, mathematical generation of part data, and AC. This adaptation would require new software, but basic machine movement techniques would remain the same. The unit is sold with direct current servos that provide direct drive to the positioning screws. However, these types of servos introduce excessive heat which can induce errors in the machine tool. The complete servo system would probably be replaced with a direct current hydraulic system.

BENEFITS OF ADAPTIVE CONTROL

AC would contribute the following advantages to an NC system: (1) machine protection, (2) part protection, (3) reduced dependence on the operator, (4) simplified part programming, (5) dimensional control, and (6) machine optimization.⁽¹³⁾ The priority and emphasis of these benefits varies considerably, depending on the application. Increased productivity obtained by machining optimization without regard to part protection, for example, would not be an acceptable solution at a plant where a single, high-cost part is being produced. A discussion of the advantages follows.

Machine Protection

NC machine tools range in price from \$20,000 to well over a million dollars. Limit controls of various types are presently being used on these tools to protect the machine and control against emergencies and unanticipated conditions of use. Some of the more sophisticated ones qualify as adaptive in nature.

Constraint limits on such parameters as spindle torque, vibration, and tool-tip temperature are not generally known to the average machine tool user. Yet, these features would serve to improve machine reliability and performance.

Part Protection

Large amounts of capital can be tied up in parts that require some type of forming or forging, various types of metal-removing procedures, and annealing

during these two processes. As a result of the speed of today's NC units, part damage generally occurs before the operator can intervene. Any form of automatic part protection would be invaluable. Devices for sensing tool forces and the cutter path provide a part protection system that would lead to considerable savings.

Simplified Part Programming

Writing a program to manufacture a particular part with an NC unit is by no means a simple task. The programmer must describe the tool path, select the tools, and establish efficient yet reasonable feeds and speeds taking into account a host of machinability considerations and workpiece/cutting-tool limitations.^(13, 14)

A system that has an AC for spindle speeds and feedrates would eliminate many programmer headaches. These parameters are a function of the workpiece material, tool type, and chip load. Generally, they are conservatively selected, but even this step requires a vast amount of empirical knowledge. A self-adjusting system would allow the programmer to specify a spindle speed and feed rate bandwidth and let the system adjust for optimum performance.

Dimensional Control

Dimensional control is one area where vast technological advances can be made. This advance would permit the making of more precise parts as well as reduce the part rejection rate.

The tool/work interface dimensions on present NC machines are not controlled dynamically. Incorrect initial tool-setting, tool-wear, and workpiece/tool-machine deflections can produce errors. Compensation can be made for some of these errors. Manually adjustable tool offsets and automatic tool setters are presently available on NC machines. However, operator participation is necessary. Also, some of the latest systems adjust for tool deflection.⁽¹³⁾

Environmental temperature changes around most machine tools induce part errors due to workpiece expansion and contraction. Under extremely variable conditions, these are almost impossible to manually correct. Errors due to temperature changes could be corrected by a computer-controlled adaptive system using the computer to calculate corrections and modifying the tool-path data for corrections. There are other temperature problems in addition to those caused by the machine environment, Richards⁽¹⁵⁾ states than on

NC turning machines, the tool-setting station was found to move 750 micro-inches with respect to the spindle in eight hours of operation due to thermal expansion of the spindle. The heat was found to come from two sources: the hydraulic spindle drive motor and the ball bearing. This heat induces errors in such parts of the machine as the spindle and lead screw. An adaptive system using laser interferometers such as mentioned by Richards can compensate for most of these errors. There is also the possibility of making corrections with the computer. By monitoring temperatures at critical areas on the machine, it may be practical to predict thermal errors and make appropriate corrections with a computer-controlled system.

Excessive cutter forces, caused by incorrect feeds and speeds or excessive tool wear, result in surface finishes outside tolerances and leave the integrity of the surface questionable. Systems that monitor forces, vibration, and wear of tools can adjust the machine drives to alleviate or minimize these problems.

On-machine inspection of parts has received wide attention during the last few years. This concept involves the use of the control mechanism to move a suitable measuring transducer to act as an in-process inspection system. A profile of the part dimensions can be stored in computer memory for reference. Automatic inspection systems would be much faster than manual methods and also eliminate the refixturing that is necessary when a different machine is used for inspection. The next advancement for a system of this type is to make a rough cut, measure the part, automatically adjust for errors, and make succeeding cuts.

Machining Optimization

Most of today's AC systems strive for a maximum production rate, a minimum cost, or some combination of these two achievements. These goals are usually realized by basing speed and feed rates on some optimization formula that uses such variables as spindle torque, tool-tip temperature, and vibration as inputs. Generally, an acceptable part is guaranteed through constraints on machine variables that are not used by the optimization formula.

This concept is based on obtaining efficient plant operation, a logical approach for most industries where mass-production techniques are demanded by competition. However, demands at some facilities are altogether different. Extremely close tolerances on part dimensions, surface finish, and surface integrity eliminate the utilization of mass production methods. It is obvious, in this case, that the greatest gains in efficiency can be attained by producing

acceptable parts that do not require multiple machining-inspection operations and by eliminating second and third finish cuts and lapping.

MACHINING VARIABLES AND THEIR EFFECTS ON KEY PERFORMANCE FACTORS

Three important performance factors are: (1) dimensional accuracy, (2) surface finish and integrity, and (3) a desirable metal removal rate. These parameters are generally interdependent and are indirectly affected by such variables as: spindle speed and feedrate, vibration, tool-tip temperature, tool wear, tool forces, environmental temperature changes, machine temperature changes, and tool/workpiece deflection. In an adaptive system it is desirable to monitor these and other performance factors. With the exception of the metal removal rate, which is determined by feedrate and spindle speed, on-line observation of these parameters has not been achieved under production or laboratory conditions. This lack of information makes it necessary to observe other indirect parameters which affect the performance factors and adapt the procedure accordingly. Most of the influential variables are discussed in the sections that follow.

Spindle Speed and Feedrate

These variables are set up by the part programmer. Their values are influenced by such factors as: the workpiece material, type cut being performed (rough, semifinish, or finish cut), shape of part, type of tool being used, or coolant being used. Any adaptive system that is developed will most likely operate on these two variables. They will be varied to obtain minimum tool forces, tool-tip temperatures, and vibration.

Vibration

Excessive vibration that originates from tool chatter and other sources causes ripples on the workpiece surface. As the vibrations become more severe, cracks and tears appear. Not only does this factor decrease the life of the tool, but vibrations can become severe enough to destroy it. Tool chatter is caused by an incorrect spindle speed. Tool feedrates can be monitored through the use of accelerometers mounted near the cutting tool for use as a feedback parameter in an AC system.

Tool Wear

Tool wear is one of the most important variables in the machining process. As the tool wears, tool forces increase, tool-tip temperatures increase,

dimensional errors are introduced, and surface finish and integrity are degraded. During normal NC operation, tool life is predicted by taking into account such conditions as: the material type of the workpiece and tool, feedrate, spindle speed, and allowable tolerances. The tool is replaced at the end of the normally predicted life to eliminate its detrimental effects. However, real time measurement of the tool life is difficult to obtain. Such indirect parameters as tool-tip temperature and tool vibration can be used to predict tool life, but these have their limitations. Introduction of coolants cloud the results when the tool/workpiece interface is used as the thermocouple, and welded thermocouples are susceptible to damage from chips being produced by the cutting process.⁽³⁾ Vibration analysis has met with some success. The General Electric Company has developed a system that monitors a certain frequency spectrum of tool vibration to predict tool wear.

Tool Forces

In any machining process, it is desirable to keep tool forces constant. This hopeful goal eliminates surface irregularities which are induced by tool and part deflection. Use of this parameter in an adaptive system can be quite profitable. For each metal-removal setup (a particular depth of cut and feed-rate), there exists one particular spindle speed that yields minimum tool forces. By using the output of a tool strain gauge as the adaptive feedback information, the spindle speed can be adjusted to achieve minimum forces. These data can also be used as a parameter to correct for errors due to tool deflection and as a parameter to predict tool life.⁽¹⁶⁾ As the tool configuration is altered through wear, cutting forces increase, causing a further change in the tool-edge tracking because of elastic distortion in the structural members of the mechanism. More power is required to remove the same amount of metal, which, in turn, exerts larger forces on the cutting tool. Experimentation on specific cutting processes will reveal the level of forces that will predict a worn-out tool.

Temperature Variations

No other single factor predominates in the geometrical control of a machining process as does the retention of an exact cutting-tool configuration. Micro-inch dimensional control of the machining process depends on temperature control whenever the materials of the system possess a significant coefficient of thermal expansion. Two approaches to temperature control are possible: (1) critical temperatures may be controlled and maintained at a standard set point; (2) critical temperatures may be measured and the desired size and shape achieved by making compensations for deviations from standard conditions. Precision production machining requires a combination of both types

of controls. Even after the utmost care is taken in stabilizing temperatures, deviations occur because of spindle-speed variations (spindle growth), feedrate changes (lead screw thermal coefficients), tool wear (worn tools generate heat which cause workpiece expansion), and other sources.⁽¹⁶⁾

An adaptive system could compensate for these types of errors by sensing temperatures and mathematically deriving corrective measures, or using an on-line part measuring system to determine the dynamic cutting parameters for dimensional error corrections. The latter system offers many attractive characteristics. It would consist of an inspection device designed around the cutting machine. Precision production systems of this type have not been perfected, but breakthroughs should occur in the near future. By storing the part profile during the cut and comparing this with a theoretical profile, successive cuts can be manipulated to correct for most errors that were introduced during the previous cut.

Tool and Workpiece Deflection

Forces exerted on the cutting tool cause it to deflect. This movement injects an undefined dimensional error in the standard NC system. Adaptive systems can remove a portion of this error. Strain gauges mounted on the cutting tool can be monitored for adaptive corrections, or real-time part measurements can be made for corrective action with an inspection system similar to that mentioned previously.

When machining thin-walled parts, dimensional errors occur because of workpiece sag. Generally, proper fixturing techniques can eliminate most of these errors for cutting machines. However, problems arise when trying to inspect these parts. A part sags due to its own weight plus the weight of the measuring device. These errors are difficult to predict but are not beyond the mathematical power of the small to medium-sized computer.

ADAPTIVE CONTROL TECHNIQUES

There are generally two philosophies pertaining to AC and computer-augmented systems. Both have sound supporting arguments. One philosophy is to use the computer as a computational tool for determining workpiece thermal-coefficient calculations, tool-wear corrections, and part-description generation while retaining all the hardware functions of the NC unit. The computer would be used to replace the tape reader, and all AC would be accomplished outside the computer. The supporting argument is that if the computer is used to replace the NC and perform AC, it will not have enough operating

time available to perform these other functions. The second philosophy is to replace the NC unit with a computer and do all AC with software.

Any computer-controlled adaptive system will use parts of both philosophies. With the cost of medium-sized computers (18 bit 8K) decreasing, any future system will probably be designed around this machine. If the computer is only used to replace the tape reader and perform the required mathematical operations, it will remain idle most of the time. Not to make use of these idle capabilities would be senseless. Replacing large portions of the NC's electronics with software will present few problems. It is, however, questionable how much of the AC can be done by computer software. In some cases speed requirements may necessitate the use of hardware adaptive features and in others this technique may be more efficient. In any case, the design should pursue the most practical method for solving a problem. The computer should not be used because of its technological appeal, nor should design concepts be followed because of outdated dogmas.

ADAPTIVE CONTROL TODAY

Adaptive control is a normal day-to-day procedure in today's machine shop. Every time the operator makes a worn tool adjustment or a programmer rewrites a part description because of errors that show up at the machine, AC has taken place. Even though these are not thought of as AC operations, they are. Any time an adjustment is made due to sensed data (eye, ear, intuition, thermocouple), an adaptation has taken place. These items are manually performed and are time consuming.

Today's research and development efforts are attempting to convert these manual AC techniques to a real-time, fully automatic system. Such items as automatic tool setters, laser interferometer feedback for correction of lead-screw errors, and those covered earlier in the report (tool-tip temperature, torque, vibration, and tool deflection) have been perfected, but are not generally included on today's production machines. In some cases, one or two of the parameters have been used on a particular application, but at this time no fully adaptive system has been developed.

Automatic Tool-Setting Device

Before a machining operation can take place, the tool must be placed at the machine/workpiece zero start position. This operation is manual on most machines, and the time required to perform this act is an inverse function of the part tolerance.

An automatic tool-setting system has been designed and installed on a NC turning machine at Y-12.⁽¹⁷⁾ Tape commands initiate an independent tool-setting cycle which automatically positions the machine slides to a fixed reference point relative to the datum and pole planes of the workpiece. Upon completion of the tool-setting cycle, control returns to the NC unit. The system utilizes a linear variable differential transformer (LVDT) displacement measuring system to detect the desired tool zero reference. The transducer is used to replace the synchro feedback devices during the tool-setting cycle where the tool cutting point is moved to a previously set reference point. Null accuracies are equal to or better than that which can be achieved by the resolution of the control system. This particular system could easily be implemented with software.

Interferometer Feedback to the Machine Tool

In a conventional NC system, feedback information to the positioning electronics originates from a resolver mounted on the lead screw. This feedback method does not include the lead screw/slide inaccuracies in the feedback loop. Appreciable errors occur in these elements after operation at high speeds over long periods of time. One method of eliminating these errors is to mount a laser interferometer measuring system directly to the machine slide and use this as the feedback element or as an error sensing device to correct the standard feedback signals. The latter method has been used at the Y-12 Plant.⁽¹⁶⁾ The measuring system has a helium-neon laser with an interferometer on each slide. The sinusoidal output of the phototransistors (mounted on the machine slides) in conjunction with high-speed bidirectional counters produces pulses which are compatible with existing control system logic. Tests run on two aluminum parts, one with resolver feedback and one with interferometer feedback, show that contour errors were reduced from 400 to 200 micro-inches and surface waviness was reduced from 200 to less than 100 micro-inches through the use of the interferometer.

Tool-Tip Temperature

Interface temperature (the temperature between the tool and workpiece) is critical for two reasons: (1) a major factor of tool wear is diffusion across the tool-chip and tool-work interfaces, and diffusion is highly dependent on temperature; (2) increases in temperature cause more heat to go into the part which makes tolerances harder to hold. Wear introduces dimensional errors and is detrimental to both surface finish and surface integrity. A variety of techniques have been used to monitor tool-tip temperature. Examples are: thermosensitive paints, infrared pyrometry, thermocouple probes, and the use of the tool/workpiece interface as a thermocouple. These methods work

satisfactorily under laboratory conditions, but most of them suffer when production environments are introduced. Use of the tool/workpiece interface as a thermocouple is one of the most efficient methods for monitoring tool-tip temperatures under production conditions. Cook and Nayak are using this method of measurement in their "activation energy" studies for tool wear rate.⁽¹⁸⁾ Bendix also used this method in their AC projects.⁽³⁾

AN APPROACH TO COMPUTER-AUGMENTED ADAPTIVE CONTROL OF MACHINE TOOLS

As stated earlier, the purpose of this report is to collate as much information on computer-controlled machine tools and adaptive-control techniques as possible. It is to be used as background material during development of a computer-augmented AC machine tool system.

It is believed that the operation of today's NC systems can be improved through use of a small, general-purpose computer as a replacement for the tape reader and a partial replacement for the electronic circuits in the NC unit. With the addition of AC, improvements could be made in part accuracy, surface finish, and surface integrity.

Development Scheme

Before any AC techniques can be implemented, a basic control system must be developed to properly position the tool with respect to the part. This step requires that software and hardware necessary for manufacturing a part be designed and made operational as Phase I of any program. Software should perform the following functions:

1. Either generate part descriptions or decode standard APT programs for machine positioning data, storing the results for later retrieval. Data will be corrected for historical machine errors at this time.
2. Control the tool position from part description data so that an acceptable part is manufactured.

The design of computer software will be compatible with AC techniques. Phase II of the program will consist of adding on-line AC. The order of parameter utilization should be as follows:

1. If positioning errors are nonhistorical, measurements will be made with interferometers for their correction. These errors include those along

the axis of movement (lead screw) as well as pitch and yaw of the tool holder as it moves along the machine ways.

2. Motor torque will be measured for the adjustment of spindle speed and feed-rates to minimize tool forces.
3. Tool deflection will be measured and used to compensate for this type of positioning error.
4. Such parameters as tool-tip temperature and vibration will be monitored for tool-wear predictions.
5. Part temperature will also be monitored for the correction of workpiece thermal coefficient errors.
6. Other machine-tool temperatures will be monitored for historical error correction due to the machine thermal characteristics.

Machine Tool

The cutting machine that is selected for use should be one that is commonly used throughout the Plant. Its inaccuracies should be large enough so that any improvements induced by error compensating systems will be detected by state-of-the-art inspection devices. One such machine is an engine lathe which has a signal resolution of 100 microinches and an absolute resolution of ± 400 microinches. This arrangement presents an ideal situation where precise parts can be produced with easily measurable errors. Any system that evolves using this machine can be applied to more accurate machine tools.

Positioning Control System

Initial efforts to improve positioning the tool should proceed with the servo system normally used on an NC machine. This system is a phase-analog servo with feedback resolvers mounted on the positioning lead screws. As indicated earlier, many machine errors are not included in the feedback loop. Any initial positioning corrections would begin at this point. Either laser interferometers, mounted to include the machine slide in the feedback loop, will be used to replace the resolver; or, if the errors are historical, they will be stored in the computer memory and used to correct the position commands to the slides.

The phase-analog control system's electronics facility is, to say the least, complicated. Critical adjustments are required to achieve maximum resolution

and minimize deadband. Phase adjustments are also very critical. The end product is a finely tuned device which can and does contribute a significant amount of machine downtime. Any improvement or design change that reduces the complicity of the system will be most helpful. This modification can be accomplished by using digital encoders for feedback or possibly by using open-loop control with digital electrohydraulic stepper motors.

Numerical Control Computational and Control Electronics

An effort will be made to replace as much of the conventional NC hardware as possible. Just how much is replaced depends on the size of the computer being used and to what extent software AC is incorporated. It is possible to completely eliminate the NC unit with computer software. This change requires extensive attention by the computer and would most likely limit computational AC. Hardware will most likely consist of counting registers for accumulating position data and generating correct pulse repetition rates for the desired slide velocities. These functions will consume large amounts of computer time when software is used for their generation.

Computer System

A computer with 8192 twelve-bit words of memory will probably be adequate although it would be desirable to have a more powerful computer such as those in the eighteen-bit-word size 4 - 8K memory range. This system would provide a more powerful tool for performing part description calculation, cubic curve fitting, and software AC. The memory system should be extended through use of an inexpensive magnetic tape or a small disc file. Either would be used for part description storage and historical error (those errors that are repeatable) data.

CONCLUSIONS AND RECOMMENDATIONS

The findings of the investigation presented in this report indicate that many advantages can be derived from the development of a computer-augmented AC machine tool system. AC will enable a higher quality product to be obtained from the fabrication process in that: (1) closer machining tolerances and finer surface finishes will be possible; (2) decreased downtime can be derived through elimination of the tape reader and simplification of the servo systems used for position control in a conventional NC unit.

Electronic technology has progressed to the point where many of the ideas proposed in this report are not only feasible, but should have been implemented before now. The time is right for the machining industry to progress into this new era of computer-augmented adaptive control of machine tools.

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