CNC Basics

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NC and CNC machines are at the heart of manufacturing today. They are the state-of-the-art equipment everybody has (or is soon going to get) that promise to lower costs, increase production and turn manufacturers into competitive powerhouses. Like many other high tech devices (such as microwaves and VCRs), lots of people have and use them—even successfully—without really knowing much about how they operate. But upgrading to CNC costs a lot of money, so it's crucial to separate the hype from the reality.

So what are NC and CNC anyway? How do they work? What are their advantages? And is upgrading my mechanical gear cutting equipment really worth it?

What is NC?

Probably the most universally accepted definition of NC is offered by the Electronic Industries Association, which defines NC as "a system in which actions are controlled by the direct insertion of *numerical* data at some point." This control can be direct wire or a number of other input media.

Numerical controls are inherently more accurate than mechanical ones and usually even more accurate than the machines they control. It is important to emphasize that NC was born out of the need for mass production, but its greatest strength and efficiency is in the production of small lots.

What is CNC?

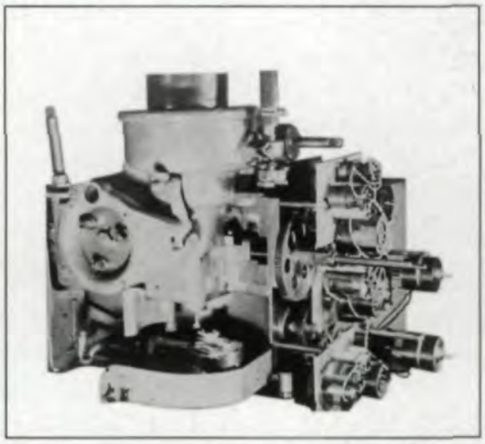
The term CNC refers to a computer attached to an NC machine. This improvement makes the machine more versatile, as programs can now be stored in the computer's memory. Instead of specially designed circuits executing instructions, a general purpose minicomputer is used, eliminating the specialized circuitry.

This "softwire" or more correctly "software" approach offers advantages over hardwired systems. For example, features such as canned cycles, maintenance diagnostics, storage of part programs and error compensation can be easily added via software. Some of the more important features of a CNC unit are memory, edit capabilities, an interface (usually a Cathode Ray Tube—CRT) with some sort of input device (keyboard) and built-in diagnostics capability.

CNC and Gear Machinery

Up until the mid-1970s gear generation equipment was controlled electromechanically. The position of the axes in the machinery was controlled by limit switches, and gear geometry was controlled by change gears. The first NC-controlled gear generation machines were relatively simple point-to-point systems.

Gear machinery manufacturers were slow to integrate NC/CNC technology into their machinery. The markets initially approached by the CNC manufacturers were the higher volume users, such as lathe and mill manufacturers, and not the low volume gear machinery manufacturers. As the lathe and mill market became saturated, CNC manufacturers looked for other markets for their controls. Even relatively small markets like gear machinery manufacturers were approached. In order to make the machinery work properly, some special functions were written by the CNC manufacturers in order to duplicate the work traditionally done by change gears. In the early years of CNC gear machinery, before these functions were freely available, manufacturers created their own hardware boards to duplicate the gearbox "change gear" functions.



Origin of the species: Modified Fellows 72 gear shaper with servomotors and film input.

Early NC hobbing machines (circa 1977) were manufactured by the gear machine tool builders utilizing proprietary electronic devices of their design, which were called electronic gear boxes (EGB), or less affectionately, the "black box." Some black boxes are still in use today in order to fulfill special functionality, but have been generally replaced with the electronic gearbox capabilities that are now built into modern CNC controls.

Elimination of the Electronic Gearbox

Up until 1980, hobbing machinery manufacturers who incorporated NC/CNC did so as an add-on to their machines designed for electromechanical control. In 1980 Pfauter introduced the first gear manufacturing machine redesigned for the CNC. Later, other gear hobbing, shaping and finishing machinery manufacturers introduced machines designed for CNC, but still used their own proprietary "black boxes."

Development of system software-based "black boxes" began at Siemens in the early 1980s. By the early 1990s, other CNC manufacturers, such as Allen-Bradley, Fanuc and NUM, got into the act.

Dr. Frederick Cunningham

The special electronic gearbox software controls the rotary functions of the gear manufacturing machines and is somewhat complex. The electronic gearbox functions needed to be built into the CNC system software before CNC machines could attain the reliability and ease-of-use of lathes and mills. After the incorporation of electronic gearboxes into the system software, the CNC systems became more "stable" and no longer relied on individual manufacturers' "black box" technology.

CNC and system software, as supplied by the CNC manufacturers, does not manufacture gears "as is." This functionality is programmed by the machine tool builders or other third party CNC system integrators. Nearly all the advantages of CNC are *software* functions, written to simplify the manufacturing process and to increase productivity.

Software and CNC

There are four different major software programs running in modern CNC machines. The first type of software is the operating system. CNC manufacturers have replaced "black boxes" and cumbersome change gears and have added an entire range of additional functions by building special software into the modern CNCs. These functions can be compared to the system software used in personal computers—for example, the DOS operating system.

The second type of CNC software is the user interface, or in PC terms, the "application software." This software is placed "on top" of the system software provided by the CNC manufacturers. Application software has many designs, names, shapes and forms: the user front end or menu, the conversational program, graphical user interface (GUI), feedback alarms, help screens. This entire range of bells, whistles, communication capabilities and graphics have made the modern machines easier to operate, given them better performance and enabled them to manufacture complex parts.

Each machinery manufacturer and CNC integrator offers his own design of application software. Gear machinery manufacturers are now beginning to introduce user interfaces that have a personal computer and Microsoft Windows™-based interfaces integrated with the CNC. Given the present level of technology and cost, the utility and economic return for these interfaces are now highly questionable. The PC front end is still more expensive, slower and more "buggy" than "CNC only"-based user interfaces.

System integrators have also been looking for a motion control system that will bypass the CNC altogether and use a personal computer for a truly low-cost motion control system. This solution has been elusive because of the need for processing speed, built-in machine standard hardware and software safety controls. Customers and equipment manufacturers currently do not wish to risk expensive workpieces and tooling on a less reliable PC system.

There is still little software standardization, and new versions are continually being produced. Gear makers will generally have an entire array of gear software on their CNC machines, which has led to some training difficulties. Today's software engineers have begun to design user interface software that is both intuitive and graphically based, reducing training from weeks to hours.

CNCs use real-time multiple operating system for multi-tasking. They are able to control multiple processes at the same time (machine functions, axis position, CRT display, etc.).

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In The Beginning Was the Weaving Machine. . .

The weaving machine and the player piano—what do they have in common? Believe it or not, they are the first true forerunners of modern numerical controls (NC).

In 1728 a Frenchman, Joseph Jacquard, saw a way to improve productivity in the highly competitive weaving business. He found that by punching holes in wooden strips he could efficiently arrange and change patterns on his looms by indicating when to change needles and threads. Jacquard patented his process and soon the entire industry changed—precision and quality improved and prices came down.

One hundred and thirty-five years later, in 1863, the Pianola, or player piano, was introduced. It used paper tape punched in patterns to play certain notes. This first known use of punched paper was the forerunner of NC tape.

Fast-forward again to the late 1940s. John T. Parsons of the Parsons Corporation (then the country's largest manufacturer of helicopter rotor blades) was working on a project for developing machinery that would manufacture templates used in the inspection of the contours of helicopter blades. Numerical control began with Parson's experimentation generating through-axis curve data and using that data to control machine tool motions. Modern NC history was made when Parsons later coupled his electronic equipment with a precision jig boring mill.

Parsons, together with IBM, proposed a development contract to the Air Force. In 1949, the Massachusetts Institute of Technology agreed to help him refine this technology. Together Parsons and MIT developed several design and safety checking features that are still in use today. (MIT actually coined the term *numerical control.)*

In 1951 NC technology was successfully demonstrated with a prototype one-axis machine. In 1952 Parsons demonstrated the first three-axis milling machine at MIT's Servo Mechanisms Laboratory. These early machines were capable of highly complex continuous path methods. (Only later were simpler point-to-point machines developed.)

Fred Cunningham's Garage

Another pioneer of NC was Dr. Frederick Cunningham. During World War II, Dr. Cunningham designed fire control systems and range finders for the Navy. Fire-control systems used the newly developed servomotors to correct the aim of the guns as the ships rolled at sea. The range finders used hard-to-manufacture, non-circular gears. After the war, being aware of the difficulty in producing non-circular gears and seeing that servo technology would be ideal in machine tool controls, Cunningham began his research in the development of NC machine tools.

Dr. Cunningham developed a non-circular gear manufacturing machine by modifying a Fellows 72 gear shaper, fitting it with servomotors and using film as the input medium. (See p. 33.) He designed a unique system to control the cutter and workpiece rotation and cutter feed simultaneously. One impulse from each control signal corresponded to one one-hundredth of one gear tooth, two minutes of arc and 0.00025". This stream of pulses would produce the gear.

The tape preparation process in Dr. Cunningham's NC was quite difficult and time-consuming. The program was manually calculated, put onto 16 mm film using a device he invented and read by photoelectric cells. This electronic device made this gear shaper the first *numerically controlled* gear manufacturing machine ever built (and the first NC machine put into commercial production.)

In the mid-1950s Dr. Cunningham put his continuous path three-axis machine to commercial use in the garage of his home. Several years later he quit his day job to devote himself to Cunningham Industries, which at the time consisted of two gear shapers, a small milling machine and some other machinery in a small shop run by his sons. Few people were interested in his gear shaper because it manufactured only highly specialized non-circular gears. However, the early continuous path NC did impress some observers, especially because of its simple elegance.

The original Cunningham NC machine is still in production today at Cunningham Industries' facility in Stamford, CT. Dr. Cunningham died in 1979, never having received due recognition in the United States for his pioneering work. But his son, Frederick E. Cunningham, continues the family tradition. He has modified the control on the original Fellows 72 gear shaper, and the original NC machine now uses a high tech, low-cost control of his and his father's design. The updated shaper is equipped with a Commodore™ 64 personal computer and stepper motors and incorporates parametric quadratic interpretation calculations to manufacture non-circular gears with the Cunningham trademark—simple elegance.

From NC to CNC

By the 1955 national machine tool show, early commercial models of numerically controlled machine tools were on display. (Commercially produced NC *gear* manufacturing machinery would not appear on the market for two more decades.)

In the 1960s the market shifted from mass production to smaller lots as consumer and industrial demand shifted toward variety. NC met the challenge of automating general-purpose machine tools for short-run production. Manufacturers began to produce universal machines to replace the highly specialized machinery previously used. (It is still a popular misconception that numerical control is justifiable only for large quantity production—just the opposite is true.)

Numerical control rapidly evolved in the control industry as well as in the machine tool industry. With the development of solid-state circuitry and modular integrated circuits, the control size became smaller, more reliable and less expensive. Although punch tape is still used as an input medium today, computer numerical control has largely replaced punched tape technology. (Even today CNC memory is measured in "tape feet" rather than megabytes.)

Today's CNC units evolved from the Direct Numerical Control (DNC) applications of the late 1960s. Early DNC systems were capable of controlling a large number of machine tools. They provided a form of tape editing at the machine tool site and collectively controlled production. With the DNC system, the tape reader was bypassed, and the machine was controlled by a host computer.

Many companies were reluctant to accept DNC because they felt it was nothing more than a replacement for a tape reader and because the technology was quite expensive and unreliable. As a result DNC was soon sidetracked by more sophisticated computer technology, which allowed control builders to incorporate computers into intelligent controls. ○

WHY CNC?

General benefits for both job shop and automated factory environments

- Mechanical kinematics are greatly simplified, providing easier maintenance; noise reduction; fewer parts for repair; easier and faster repair in case of failure; higher productivity; higher speeds and feeds; less heat generation and machine expansion; dry cutting capabilities due to higher speeds; quick setup; less idle time between changes in workpieces; easier, faster and more accurate entry of data parameters; easier repeated setup because data parameters are stored in memory.
- Complex workpieces can be made in one machine setup, using multiple (gear, tool, process, setup and cutting) cycles.
- Modification of tool path is simplified—standard canned cycles for crowning, end relief, taper, etc.
  Custom specific cycles can be easily edited.
- Machines have active (measured) or passive (estimated) compensation for tool wear and temperature stability.
- CNC machines are capable of implementing standard computing programs for the calculation of optimal tool usage with optimized feeds and speeds and the prediction of quality and part tracking.
- Inspection is simplified.
- Easier monitoring of machine status is possible.
- Machines have extensive diagnostic capabilities.
- Graphical user interface capabilities allow operators to view and input part, process and tool data on screen in the same perspective as they would normally view a blueprint.
- Easier operator training provided through help screens, graphical user interface and conversational input.
- Scrap reduced because of fewer errors in production.
- Production planning improved because machines are less specialized.
- Less space and smaller inventory required.
- Menu input is easily switched between inch and metric.

Additional benefits for automated factory environments

- Unmanned production capability; 12/24 hour production.
- Automatic retooling and refixturing capability.
- Networking capability (connection to host computer).
- Online gaging capability with corrective feedback.
- Tool management capability in the CNC or coded on the tool itself.
- Adaptive feed and speed control capability.
  Higher production output.
  Tool breakage monitoring.
- Machine diagnostics with graphing capabilities.
- Simplified interface to robot, gantry or other loading systems.
- Machines require less floor space due to simplified kinematics.
- Access to data entry screens can be optionally inhibited.

The third type of software used in CNC machines controls the tool path of the machine–the "parts program." This software is the heart of the CNC and is provided by the CNC manufacturers. (The program is in principle a code that in the past was fed by punch tape because the NC did not have sufficient memory.) The parts geometry is obtained by keyboard input or communicated to the system from a central computer and is fed to the parts program software to instruct the CNC.

The fourth software, called the programmable logic control (PLC), is integrated into the CNC and controls the machine logic. This software code polices the machine functions. For example, the PLC program will normally check all preconditions in order to start the parts program. It will also stop the machine if a door is open or if other safety devices are tripped. The PLC program utilizes a standardized coding scheme called the "ladder" program. The ladder is programmed by a system engineer who must fully understand the specific gear machine functionality.

What Does the CNC Do?

Without CNC controls, a machine operator must create a step-by-step procedure for making a piece by deciding which surface to machine first and planning all the motions, cutter speeds and feeds to make the final product. The product quality depends on the skill and speed of the machine operator.

With CNC, once the procedure and tools have been determined, the CNC machine operator makes the same part over and over in exactly the same way without human intervention. A skilled operator running a manual machine will be cutting a gear at most 30–40% of the time. With a modern CNC machine, cutting time can be improved to 70–90%.

CNC does not totally eliminate the need for skilled operators. If necessary, the operator may still manually control the machine with the use of jogging switches, hand wheels, or Manual Data Input (MDI). This versatility is a benefit of the technology. Machinery can be designed to run automatically or with a great deal of operator interaction, depending on the customer requirements.

Why Use CNC Gear Machinery?

Many gear shops are still quite happy with their old electromechanical machines and wonder why they should upgrade. Investment in new gear-making machinery is quite expensive, and there are arguments against it.

One problem with CNC is that the technological life cycle of each control is relatively short, only about 10 years. The actual usable life is of course much longer, but CNC, like any microprocessor-based device, advances in technology very quickly, and investment in newer versions of CNC technology will again be justifiable in about 10 years. This would not be much of an issue except that the mechanical portion of the gear machinery has a much longer life, up to 30 years, and can be extended almost indefinitely by overhaul and rebuilding.

One reason for changing to CNC-based machinery is that current electromechanical machines will not last forever. Furthermore, these machines simply cannot manufacture gears cost-effectively anymore. Parts for mechanical machines are also becoming harder and more expensive to locate.

Although change is inevitable, many users are putting it off as long as possible. Changeover to CNC machines is not so much a question of why as much as when. In order to stay competitive, more efficient manufacturing technologies need to be used, and in the gear industry that usually means updating of equipment incorporating modern CNC technology.

An analogy can be drawn by comparing the purchase of an old mechanical typewriter to a modern PC. The cost of PCs is low, and their reliability is acceptable; plus, the PC can do the word processing—and a great deal more! Furthermore, the development of user-friendly, easy-to-use graphical and conversational interfaces makes PCs easier to use all the time. Fewer and fewer reasons remain to delay the move to CNC.

Another reason why a switch is necessary is that the parts that gear manufacturers are producing are much more complex (as compared with only 20 years ago), and the tolerances are getting tighter. New gear designs always seem to push the envelope of the CNC's capabilities. Many of these advanced parts simply cannot be made on electromechanical machines.

The level of operator and engineering personnel skills required to properly manufacture these complex parts is considerable, and fewer skilled gear makers are available. CNC-based gear manufacturing, with the capability to program and modify the tool path, does greatly simplify the manufacturing process.

An additional incentive is ISO 9000. U.S. gear manufacturers who wish to improve the quality of their products know that CNC manufacturing techniques are a wise investment. CNC manufacturing systems are especially useful for shops that need to track each part as it moves through their facility.

What About Retrofitting?

The question many job shops now have is whether to buy a new CNC machine or perhaps one of the early generation of NC machinery. The answer may depend to a good extent on the kind of machine under discussion.

Converting a mechanical "change gear" machine into a modern CNC machine is a costly proposition because of the relatively complicated kinematics that need to be redesigned. Only unusual configurations or larger-sized versions of these mechanical machines, which are generally expensive to replace with new machinery, can be cost-justified. On the other hand, updating an early NC/CNC machine already designed for NC controls is a much less painful proposition. Modern CNC machine kinematics are much simpler (think of a mechanical watch with gears compared with the much simpler kinematics of an electronic quartz watch), and therefore easier to build. As CNC technology has advanced, the mechanical portion of the machines has decreased.

Conclusion

Gear makers will not be able to avoid the switch to CNC machines much longer. When the mechanical machines in shops are scrapped, CNC-controlled machines will take their place. Gear makers who do not invest in the technology are falling further behind and widening the technology gap that will eventually need to be bridged. ○

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