Coordinate Measuring Machines and the Gear Industry

Charles Cooper

Gears are extremely complex shapes. Coordinate measuring machines, or CMMs, are designed to measure complex shapes. It seems to follow that CMMs would, therefore, be the ideal tool for measuring gears. But the answer is not so simple.

While coordinate measuring may be the preferred way to quickly and accurately inspect bevel gears, manufacturers of parallel axis gears have long relied on their spline gages, roll testers and mechanical elemental gear checkers for involute and lead inspection. More recently, they've added CNC generative gear testers and single flank inspection machines to their repertoires.

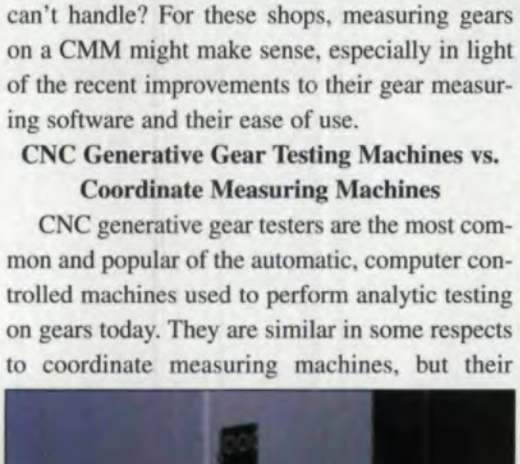
But what about shops that make all types of gears, or shops that need to measure splined shafts, gearbox housings or other custom components that a dedicated gear inspection system can't handle? For these shops, measuring gears on a CMM might make sense, especially in light of the recent improvements to their gear measuring software and their ease of use.

CNC Generative Gear Testing Machines vs. Coordinate Measuring Machines

CNC generative gear testers are the most common and popular of the automatic, computer controlled machines used to perform analytic testing on gears today. They are similar in some respects to coordinate measuring machines, but their design and programming are strictly attuned to testing gears. According to Mark Cowan, director of metrology for M&M Precision Systems of Dayton, OH, "CNC generative gear testers are considered to be the fastest, most precise way of measuring parallel axis gears." Considered turnkey systems, these machines are made so that the machinist on the shop floor can enter the necessary data and test the piece he is working on in accordance with AGMA standards. These machines are called generative because they work in much the same way as their mechanical predecessors, using a probe to physically trace out, or generate, the involute shape and lead. According to Cowan, the process of CNC generative testing works like this: "To measure an involute, the probe is positioned at the base radius of the part and then driven along the linear tangential axis at the same tangential velocity as the rotary at that radius. So, you have a mechanical linkage that drives the probe along and actually generates the profile. The probe is actually scanning along the involute, measuring deviation or error in the tooth form."

On the other hand, a coordinate measuring machine records numerous axis positions as data points, which are then used to build-up the 3-D model of the part. "That's a more complicated process," said Cowan, "because it's almost like measuring the part backwards. What the CMM does is move the probe around the tooth flank in some given plane. Then it fits a theoretical form around that plane and computes deviation from that. For example, say you're moving a probe from the root diameter to the OD. If you're on a helical part, the actual place where the probe is contacting is moving because the helix angle on a gear changes when you go from the root to the OD even though the lead stays the same. You have to compensate for that. Unless you have a canned program written by the CMM manufacturer, it's not a simple thing to program a CMM to measure a gear."

Above: Spriral bevel gear being inspected on a CMM. Courtesy of Brown & Sharpe.



Right: Worm being inspected on a CMM. Courtesy of Brown & Sharpe.

Because of this complexity, which offsets the flexibility that is the main strength of coordinate measurement machine technology, the machines are considered by many to be too difficult to use for regular shop floor personnel. According to Robert E. Smith, president of R.E. Smith & Co., Inc., a Rochester, NY-based gear metrology consultant and the co-chair of AGMA's Inspection and Handbook Committee, "CMMs are very capable machines and can be very accurate. But to me, it takes more of an engineer to run that machine than a shop person. If you have a CNC generative machine, most of the shop people would be capable of running that." The reason, according to Smith, is the complexity and user-hostility (as opposed to user-friendliness) of the programming, and the time and skill it takes to set up and calibrate the equipment. "I have lots of problems with the [CMM] gear software," said Smith. "For example, with some software you can't input DP. It's written for module. So, if you're doing a gear here in the U.S., and it's the DP system, why should a guy sit down with a hand calculator when he's got this big computer sitting there?"

Of course, not everyone agrees with this perceived user-unfriendliness. "Ten years ago, you'd have to sit down and write a Fortran program," said David Genest, director of marketing and corporate communications for Brown & Sharpe. "Today it's much easier. You can download CAD files or use application-specific software." As compared to CNC generative testers, Genest sees the two technologies and their driving software as fairly comparable, the only real difference being the familiarity of gear people with gear machines.

CMM Advantages

Coordinate measurement machines have a number of applications and advantages that gear manufacturers should understand and consider. These can be divided into two broad categories: bevel gears and quality control.

Precision Bevel Gears. One area where coordinate measuring machines are needed is with bevel gears. According to Cowan, the main reason why CMMs are preferred for this work is that bevel gears are not easily described in 3D. "The normal vector is constantly changing in three dimensions as you move from one place to the next on the form of a bevel tooth. You can't really generate the motion, so you have to go to different points to take it [the measurements]." Having to rely on data points means having to rely on coordinate measuring machines to get the job done. Smith agrees. "If you want to measure a bevel gear tooth shape, a coordinate measure-

HYBRID MACHINES—GEAR TESTERS OF THE FUTURE?

There is an emerging class of machine that is neither a true coordinate measuring machine nor a true CNC generative gear tester. These machines are attempts to combine the best features and abilities of both machine types in a single, integrated system that offers true, three-dimensional volumetric capabilities.

Next Dimension. Still undergoing beta tests, the Next Dimension 430 from Process Equipment Company is a dedicated gear tester that mixes CMM and generative tester technology to produce a very flexible gear metrology tool. According to Dick Considine, the software engineer on the ND 430 project, "The ND 430 is a volumetrically mapped coordinate measuring machine that is designed to do gear inspection." The difference is that this machine can measure features on a gear that traditional CNC generative testers cannot in ways that other gear testers cannot. "CNC generative testers can give you relative measurements," said Considine. "We can give you absolute and relative measurements."

The software driving the machine is a Windows 98-based package that is entirely configurable to the customer's needs. "With gear systems, one of the things in the industry is that most software packages out there haven't been designed. They have evolved. They've been around for a long time and they've been added to until there are now hodge-podges of stuff out there. Our system is brand new, the software totally rewritten and it's fully compliant with all three standards—ISO, AGMA and DIN."

Because it is so early in the machine's existence, the engineers at Process are still figuring out all the applications that the ND 430 will be able to perform. "In addition to gear measurement," said Considine, "it will be able to do a lot of other things such as measuring cams relative to gears, keyways relative to gears and gears relative to gears on the same assembly. Normal gear machines can't do that."

Radiance 1006. The Radiance Radial Measuring System is designed primarily for rotary tasks. While this naturally includes gears, the Radiance is not restricted to them. Rather, the machine is capable of scanning a variety of cylindrical and rotary parts as well as hobs, shafts, cams and other pieces. According to Jack Epstein, TSK product manager and the developer of the Radiance concept, the Radiance was developed to solve the problem of dual machine use. "Companies often use generative gear testers as well as CMMs to check their gears," said Epstein. "That's extra expense, extra training and extra floor space. The Radiance solves all that."

For gear makers, the Radiance offers a lot. The machine can measure all the features of a gear including teeth, faces, shafts, bolt hole circles and more. In fact, it has been designed to inspect any feature on a gear that needs verification. Users only have to learn to use a single software package, and the unit is as comfortable on the shop floor as it is in the lab. Added to this, the great flexibility the machine gets from its CMM ancestry makes it a very powerful tool to have in the shop. "The machine is best suited for rotary or cylindrical parts," said Epstein. "it can handle anything up to a meter diameter—gears, shafts, hobs—without fixtures. The machine senses part orientation and measures normal to any feature with the probe traveling 360° around the stationary part."

These two machines are both precise instruments capable of micron-level resolution and both are programmed to give gear people the information they need to qualify a part or to adjust machine tool settings. While all of this is promising, they are also both very new.

The Radiance Radial Measuring System. Courtesy of TSK America.

"A CMM typically used to measure prismatic parts can, in an instant, be used to measure gears, " said Rolf Dettler, an applications engineer for Carl Zeiss. "For manufacturers of both items, it is an ideal solution. The capital investment is far less than buying two separate machines."

ment machine is the way to go. But it's a special machine, special software, it's expensive. The only people who'd have it are your aircraft or automotive people."

One example of a gear maker using coordinate measuring machines is Aero Gear. This Connecticut-based gear manufacturer for the aerospace industry sees their Brown & Sharpe Chameleon® coordinate measuring machine, which they use to check spiral bevel gears, as a major plus to their operation. The Chameleon® is equipped with Brown & Sharpe's Quindos software, programming that is specifically designed to interface with their Gleason Phoenix grinder's Super G-AGE system. According to Carl Russo, a process engineer for Aero Gear, "Ease of setup prompted us to use CMMs. We do mostly small quantity jobs, and we needed a fast way to inspect gears and splines. Once you create a program, you can check parts much quicker."

Aero Gear's coordinate measurement setup allows them to maintain tight process control by feeding the data from inspected parts directly into the gear grinders. "We get these coordinate point files from The Gleason Works so we can make our own summaries," said Russo. "Then we get a coordinate file for the CMM and measure the topography of a workpiece on both sides. Then, after the machine has done that, we have it measure the pitch error and runout." More measurements and calculations are made to create what has come to be called a digital or theoretical master. "We create the so-called theoretical master file," said Russo. "Depending on the customer requirements, we'll get their reference master and measure that relative to the coordinate file we calculated and alter that original file to match the customer's actual master."

Next comes the comparison of a production workpiece with this digital master stored in the CMM's computer. By comparing the workpiece to the digital master, the machine generates an error data file. This error file, which details how far the dimensions for each tooth vary from nominal, is then fed into the Phoenix machine's Super G-AGE system software. The G-AGE system then creates a correction file that changes the grinding summary for the machine, correcting the errors.

General Quality Control. This area includes fulfilling vendor certification requirements, checking the quality of parts shipped, process monitoring and control, tooling qualification, tool wear monitoring and gage qualification. In many areas, CMMs are considered the method of choice for quality control applications. They can test manufacturing processes for dimensional accuracy, perform statistical certification of part quality, detect tooling problems, recertify gages and other measurement tools, and use dimensional data to find and correct problems in the manufacturing process.

At Aero Gear, the CMM has the first and last word on quality control. "The gear grinder or gear shaper will make a first piece, and then we'll have a first piece inspection on the CMM," said Russo. "Then, as the operator runs the part, we'll generally use a spline gage or roll the parts on a redliner to monitor the quality. Then we also do a last piece inspection so we have first and last piece element charts. If it's a large quantity, we'll do a couple a day on the CMM."

CMMs In The Lab and On The Floor

Over the years, as CMM technology has become more accessible to machine tool operators and others working on the shop floor, the amount of training needed to operate coordinate measurement machines has been greatly reduced. There are those in the gear industry who might disagree with that assessment, but the trend toward easier programming and greater accessibility is certainly there.

The programming also allows coordinate measurement machines to be automated. This, and advances in machine design and construction, has made it practical to take coordinate measurement machines out of the lab and place them on the shop floor.

Lab CMMs. Gear metrology labs are clean, climate-controlled rooms designed to limit or eliminate environmental variations in measurement results. This level of precision and control is needed because lab machines are used more for troubleshooting and inspection.

Portal machines are one example of a dedicated laboratory CMM. Highly accurate machines, Portal machines utilize a moving granite base rather than a moving bridge. This provides greater accuracy and movement control than is possible with a moving bridge. "They tend to be larger," said Genest. "They tend to be made out of granite, not aluminum, and they're slower than shop floor machines."

Shop Floor CMMs. Coordinate measuring machines on the shop floor are a hardier breed, better able to deal with the heat, dirt and vibration associated with active machining operations. These machines are used primarily for process control in large automotive and aerospace shops to check parts during a production run. "Generally, they're automatically loaded and driven," said Genest. "The part programs are downloaded when

CMM inspecting a spur gear. Courtesy of Carl Zeiss, Inc.

the parts arrive and all the operator does is say, 'run.' All the programs are generally done up front because the machines in the factory come with all the fixturing and all the parts programming in place. It's a turnkey. The user interface is like a McDonalds interface: I got part 12, I want to inspect it, run."

Shop floor machines are designed to be clean, fast and to adapt to temperature changes. They are made of aluminum because granite absorbs oil, is slow moving and changes with temperature very slowly. "Years ago," said Genest, "we thought that was the cat's meow and aluminum was the scary stuff that changed very rapidly. But that's what you want in a shop floor machine. When the temperature changes you want the machine to change instantly. You don't want it to be slowly twisting and turning. You want to design a machine that doesn't twist, that just grows longer or shorter. It's very easy to compensate for that."

Accuracy and Tolerances. The major difference between shop floor CMMs and laboratory machines is accuracy. For coordinate measuring machines, precision is measured in terms of volumetric accuracy—the total cumulative error of all measurements taken along all three axes. According to Genest, the very best lab CMMs have a volumetric accuracy to under 1 micron, while their shop floor counterparts are, at best, accurate to under 10 microns. This is a very important distinction given the way tolerance measurement works.

"If you have a tolerance of a part that's 10 microns, a very tight position tolerance, you need a machine that's ten times more accurate than that tolerance to really resolve whether it's right or wrong," said Genest. To be certain that a part is within tolerance, your measuring equipment has to be far more precise than the tolerance you are looking for. "The problem," said Genest, "is that tolerances are getting so tight now that the 10-1 rule is now threatened. It's down to 5-1, or maybe 3-1 now." For gear manufacturers, that means the tolerances being demanded today are reaching the limits of the measurement precision of the machines. If this trend continues, it will raise the question of uncertainty as to whether the part is really within tolerance. "The lower you drop it," said Genest, "the more you run the risk that you are shipping bad parts." When it reaches 1-1, the uncertainty of the measurement will be 50%, meaning that accuracy and tolerance will be a coin-toss.

Costs. According to both Cowan and Smith, the kind of coordinate measuring machine that would be useful to gear manufacturers, one with a rotary table, scanning probe, sufficient precision and the right software, would be as much as or more than a generative gear tester, somewhere in the $300,000 to $500,000 range. "That does not include the cost of training the operators," said Cowan. "When you buy a dedicated gear inspection system, it comes with any training that's required, typically only a couple of days." With some brands of CMM, it's much different, Cowan said. "You have to take an operator and train him for at least a week, if not more, in order to be able to learn the language to write part programs."

According to Genest, the cost of a CMM is comparable to generative gear testers, and Brown & Sharpe includes all the hardware and software, as well as installation, documentation, certification, calibration and training. "The training on the CMM software takes about a week," said Genest. "If you were a gear manufacturer, you would probably then take an advanced course in the specific gear applications you would be working with." For that operator to take a part that's handed to him, throw it on the machine and measure it in under an hour can take six months. "It depends on the operator's expertise," Genest continued. "If you have someone who is very computer literate and has a firm grasp of the three-dimensional aspects of geometry, then it goes a lot quicker."

Comparable machine costs means that even with the added training required for specific applications, a gear manufacturer who also makes shafts and bearings, gear boxes or other parts may find that the CMM is more economical due to the machine's greater flexibility. "A CMM typically used to measure prismatic parts can, in an instant, be used to measure gears, " said Rolf Dettler, an applications engineer for Carl Zeiss. "For manufacturers of both items, it is an ideal solution. The capital investment is far less than buying two separate machines." All they would have to do is program the machine to examine their products, and there are software packages available from a variety of sources including Brown & Sharpe, Zeiss, The Gleason Works and others, to make that programming easier. On the other hand, dedicated gear shops that make parallel axis gears would likely find CNC generative gear testers, machines designed and developed to work exclusively with gears, better suited to their operations.

The Future of Coordinate Metrology: Digital Masters

One of the reasons that coordinate measurement technology has become so important to the gear industry recently is the 1998 determination by NIST and the Department of Defense that electronic master gears are a viable adjunct to the physical master gears used for final acceptance decisions relating to

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CNC generative gear tester. Courtesy of M&M Precision Systems Corp.

THE BASICS OF COORDINATE MEASURING MACHINES

What precisely is a coordinate measuring machine? The most basic definition is a machine, either manual or automatic, that takes measurements along three axes to define a three-dimensional shape using a sensor, called a probe, that is brought into direct contact with the object being measured. The probe contacts discreet points along the surface of the object, a gear for example. Measurements are taken from these data points, run through the CMM's software and related to a three dimensional Cartesian coordinate system. The accuracy of the CMM is governed, in part, by the machine design itself, but mostly by the type of probe being used.

Probes. Manual coordinate measuring machines use hard or fixed probes (ball, tapered plug or edge). These are placed in contact with the part to be measured by the operator, who then manually initiates the taking of the measurement. The next step up is the touch-trigger probe, which closes a switch when it contacts the part. This is more accurate, and the feedback generated by this kind of probe is what allowed DCC (direct computer control) of CMMs. Perhaps the most sensitive kind of probe is the continuous scanning probe. This kind of probe does not measure separate data points like the touch-trigger or fixed probes. Instead, it measures the deflection of the probe pin in all three axes. This allows the machine to compensate for any deflection during the measurement process while providing feedback for continuous scanning. Continuous scanning means that the probe follows the contours of the part being measured. This collects a great deal of data, far more than touch-trigger or fixed probes can provide, making it useful for inspecting variable part geometries.

More exotic, non-contact methods such as electro-optical sensors or lasers are used when a physical probe isn't practical or in applications where the part being measured cannot be touched. With electro-optical sensors, an image of the part is compared to a digital master stored in the CMM's memory. Lasers are another method of noncontact coordinate measurement. "They work like a touch probe," said Mike Berlin, U.S. product manager for Mahr. "The laser generates discreet data points in the X,Y and Z axes based on the reflection of the laser from the part being scanned." These data points are stored in the machine's computer and the 3D model is built up in the usual way. Lasers, however, are limited to materials that offer enough reflectivity to produce a viable return.


CMM Probes and gears. Courtesy of Brown & Sharpe.

Construction. There are various types of coordinate measuring machines on the market today including fixed and moving bridge type machines; cantilever, gantry and column machines; single and dual horizontal arm machines; and measuring robots. Still, all have certain things in common. Typically, the machines have a heavy base, usually granite, that is either placed on the floor or fixed to it. This supports the part being measured. Over that, depending on the design, there are rails and carriages that move the probe in any of the three axes. In bridge-type machines, for example, there would be Y-axis rails attached to the base. The bridge, holding the rails and carriage for the X-axis, would move along these rails. This, in turn, supports the Z-axis and the probes. Air or roller bearings are used, depending on the environment, to provide smooth movement through all three axes. On some highly accurate laboratory machines called Portal machines, the bridge remains motionless while the granite base moves. While slower, this is considered more accurate and repeatable.

Positioning is determined by the measurement system within each of the axes, often glass scales mounted on each axis with an electro-optical system that uses light reflected off the scale to read the position.

Programming. Finally, there is a computer to collect and process the measurement data. The software used by these machines is such that a part's data can be programmed into the machine to be used as referents for the part being measured.

The software found in today's CMMs is modular and easily interfaced by icon or menu-driven operating systems. Additionally, the software found in many CMMs today is capable of statistical analysis, mathematical computations, links with CAD, CAE, CAM and other outside systems. Some CMM software packages include special purpose analysis and application modules including real-time statistical analysis, flexible gaging, best-fit analysis, and contour measurements and comparisons.

All of this makes coordinate measuring machines extremely flexible. According to David Genest, director of marketing and corporate communications for Brown & Sharpe, "They can measure any part that will fit into the machine, making them ideal for manufacturers who produce many different kinds of parts."

Combination video, laser and touch probes. Courtesy of Mahr Corporation.

precision spiral bevel gears and that such digital masters will play a greater role in the future.

In a sense, coordinate measurement machine technology is based on the idea of a digital master. In order for the machine to perform the inspection of a part, it must be able to compare the measurements it takes from the production piece with a set of nominal values. Whether those values are fed into the CMM's computer manually, through a first piece inspection or are derived from a CAD drawing, the result is the same—a range of nominal data that performs as a master part. Because these data points are precise measurements, the same level of interpretation is not required as with other kinds of testing, e.g. roll testing, where marking compound is applied and the results interpreted.

The DoD report, called "Electronic Gear Master State-of-the-Art Review," was sponsored by the U.S. Army Aviation and Missile Command and carried out by the IIT Research Institute and INFAC, the Instrumented Factory for Gears. The report was published in September, 1998. The study was based on the need to reduce the cost of helicopter transmission components. The method under consideration in the study was the elimination of physical master gears. According to the report, "Inspection and testing are major cost drivers in the production of precision gears, especially spiral bevel precision gears, and represent a key target for reducing the cost of helicopter transmission components."[1] There were three objects of the study. The first was a feasibility study of eliminating physical gear masters from precision spiral bevel gear manufacturing. The second was the development of a standardized methodology for inspecting spiral bevel gears as a potential approach for using CMM technology for final part acceptance. The third object was to define an approach for establishing and defining a standard methodology, procedure and technology for allowing the use of coordinate measurement machines for final acceptance of precision spiral bevel gears.

The focus of the study was precision spiral bevel gears. For the study's purposes, precision was defined as AGMA 12 or greater. During the survey it was found that digital masters based on coordinate measuring machines do offer lower costs, greater flexibility and better documentation of the desired engineering configuration. It was also found that the CMM was able to eliminate the subjectivity of roll testing.

The report concluded that "The use of coordinate measuring machine technology has made a tremendous impact on the manufacture of precision spiral bevel gears, resulting in higher quality and lower cost." The report also concluded that "it is further evident that electronic masters may play a greater role in future gear designs, but the precision spiral producers and users will always want a physical master."[1]

Conclusion

Coordinate measuring machines may be a long way from displacing CNC generative gear testers, but they are making a great contribution to the gear industry, especially among aerospace and automotive manufacturers. The idea of the electronic or digital master gear is being explored while probe and sensor technology, as well as CMM software, are being improved. Combined, these developments promise growth in the use of a machine that is, today, already as ubiquitous in industry around the world as any other machine tool. ○

1. INFAC. "Electronic Gear Master State-of-the-Art Review," Sept. 1998.

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