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Volumetric error compensation technology developments are gathering pace. Andrew Allcock explains the background and reveals who is doing what and with what benefit [extended version of magazine feature - UPDATED SOMMACT project information - 12 May 2010]

Recent announcements/developments in this area have been made by the likes of machine tool makers MAG Industrial Automation Systems of the US and Japan's Makino; CNC makers Siemens, Fanuc and Heidenhain; measurement technology specialist Renishaw; and the UK's Huddersfield University's Centre for Precision Technologies. One industry insider describes this area as "the next big thing".

Incidentally, when talking about volumetric error compensation, we are talking here about prismatic machining, 3-axis and 5-axis – horizontal turning or mill-turn machines do not feature in anything Machinery has so far seen.

ERRORS ARE UNAVOIDABLE

All machine tools exhibit repeatable, albeit small, geometric errors. The effort to further reduce their effect is mainly driven by the aerospace sector, and by the need to machine large, complex monolithic parts. In particular, the US-led Joint Strike Fighter (JSF – F-35 Lightning) programme is cited. This involves a number of international suppliers, and demands high precision production of parts to support interchangeability and minimise assembly fitting. Indeed, lead partner Northrop Grumman publicly recommended Siemens' volumetric error compensation capability –VCS - for the F-35 supply chain in June of last year. "Extensive on-machine testing and evaluation by Northrop Grumman has demonstrated that a quality machine tool appears to be made substantially more accurate by using the Siemens VCS feature of its Sinumerik 840D solution line CNC," it said. The general manufacturing tolerance figure banded about for F-35 and referenced by those in the machine tool industry is 50 microns.

Image: **Lockheed Martin leads the international F-35 effort, which requires high levels of precision.**

Control maker Siemens' (0161 446 6400) Dr Jochen Bretschneider, manager, value added services, says that other markets, such as the automotive, energy, mould and die, as well as ultra-precision machining, are also expressing interest in VCS, launched in August 2008. The company has a number of end user installations already in place.

Currently, the improvement in volumetric accuracy for a given machine tool with VCS is at least 50 per cent, with the result for highest quality machines (those with highly repeatable errors) better than that, offers Dr Bretschneider. Importantly, VCS is not a tool to make mediocre machine tools high accuracy ones, it is highlighted.

Typically, machine tools have their linear positioning errors measured by builders in the X, Y and Z axes (plus rotary position axis errors in A, B or C), with this then used to support linear/rotary position compensation within CNC units. This is compensation for the difference between programmed and actual linear/rotary position. The post-compensation figures for linear/rotary accuracy and repeatability are what all machine tool builders then quote; they do not quote volumetric figures, which are clearly larger.

To achieve acceptable volumetric accuracy figures, machine tool firms machine parts and assemble machines accurately by making sure that surfaces, locations and features are variously: accurately aligned; parallel; perpendicular; flat; straight; and true.

To assure themselves that this is so, they undertake tests to identify errors in the working volume. These are not used in any CNC-based compensation. However, they are just used as an internal measure against in-house requirements and are not publicly quoted. But, fundamentally, for any single linear axis, there are more error sources than simple linear ones and it these other errors that volumetric error compensation technology additionally addresses.

In a 3-axis machine tool, there are 21 sources of error related to the axes. The 21 are: linear position; roll; pitch; yaw; plus vertical and horizontal straightness in each linear axis; plus the three squareness errors, X-Y, X-Z, Y-Z. To complicate matters, there are non-mechanical errors, such as servo mismatch, but these are compensated for by 'servo tuning', available in all machines.

Image: **Each linear axis has six geometric errors. Technology such as Siemens' VCS can compensate for these.**

Now, if you add two rotary axes (5-axis machine), the mechanical error count gets up to the commonly accepted 43, although 52 are instanced by German measurement technology firm Etalon, which operates in the area of machine error measurement (see later). Heidenhain's Dr Jens Kummetz elaborates. "Etalon is also counting the four location and five component errors of the main spindle. The five component errors of the spindle cannot be compensated for, however.

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This is because the high rotation speed of the spindle would require high speed axis moves to provide such compensation."

Siemens' Dr Bretschneider explains that a number of compensations have been available in its Simumerik 840D for many years, prior to VCS. So there's beam/ram sag compensation, offering two-dimensional, inter-axis compensation and also so-called 'cross-error compensation', which arbitrary user-defined inputs to generate an output.

With VCS, all 21 errors can be compensated for in a 3-axis machine. When considering 5-axis machines and employing Siemens' TRAORI control feature, 14 errors in the rotary axes can be compensated for. With VCS and TRAORI, Siemens can currently compensate for 35 errors in 5-axis machine tools. But Siemens CYCLE996 offers a means to quickly compensate for rotary axis errors. With the aid of a calibration ball and a calibrated probe, this supports automatic measurement of rotary axis vectors. After the measuring process, the correction values can be entered to effect digital alignment of the rotary axes (see video here).

Heidenhain CNCs (01444 247711) similarly sport compensation technology, KinematicsComp, launched in 2008, and KinematicsOpt, launched this year. The former is for use on both 3 and 5-axis machines, and the latter adds additional rotary axis error compensation. With these two technologies, Dr Kummetz says that 47 error sources can be accommodated in a 5-axis machine (KinematicsOpt added the capability to compensate for the four spindle location errors; prior to this, KinematicsComp tackled 43 error sources). It handles all 21 in a 3-axis machine, of course. No examples of its technology in action are revealed by Heidenhain, however.

Image: Heidenhain's latest addition to its error compensation portfolio is KinematicsOpt. This complements its existing KinematicsComp technology. With these two capabilities, 47 errors can be compensated for with its TNC controls.

Control maker Fanuc (01895 634182) has also recently expanded its control's error compensation capabilities. Last year, it announced the extension of its 3D error compensation function, with the addition of 3D rotary error compensation for its 30i and 31i-A5 CNCs, which already had linear axis volumetric error compensation. The benefit of the new development was highlighted by Fanuc observing that, if the angular error between tool and workpiece is approximately 0.0015° (15"), the upper opening of a 300 mm deep hole is approximately 8 µm larger than the lower opening. (Incidentally, Japanese machine tool maker Makino, which uses Fanuc controls, launched its MAG 7 horizontal machining centre last June, a feature of which was volumetric error compensation capability. The machine has axis travels of 7,000, 2,500 and 1,000 mm in X, Y and Z.)

MEASURE FOR MEASURE

But, regardless of the availability of the CNC technology, a barrier to application has been the time required to measure the errors in a machines working volume, these needed to populate a CNC's compensation table. And it is here where further developments are taking place, in the methodology and instruments used.

You can take error measurements singly, measuring them individually, one at a time, using a laser interferometer, for example. But this is lengthy; many days or weeks, some say, although this is challenged – see later. But there are other, claimed much faster methods that employ a laser tracker located on the machine bed, together with a spindle-located target – Germany's Etalon and America's Automated Precision Inc (API) offer such systems (See here for more detail on the Etalon approach).

In these, information on a number of parameters is gained simultaneously, with the collected data processed by software (maths) to generate (deduce) data relating to the individual error values. Using Etalon's TRAC-CAL and related software, for example, the time needed for a full error mapping of a 3-axis machine would take from 1 to 3 hours, it is claimed, while volumetric accuracy improvement of between 50 and 80 per cent is claimed by Etalon for 3-axis machine applications.

But the areas of measurement method and subsequent data processing are not without controversy. For example, in 2004, Renishaw (01453 524524) challenged what is known as the body diagonal measurement method (part of the B5.54 and ISO230-6 standards) that relates to a speedier method of measurement of volumetric accuracy, using laser interferometers, highlighting that: "Estimates of volumetric or machine performance that are based on diagonal tests alone are unreliable…The results of a diagonal test in isolation cannot be used as a reliable machine comparison index." (See report here).

Renishaw's Ralph Fergusson-Kelly, marketing manager for calibration products, says that he believes that this led to a modification of the process to incorporate additional measurements, which reduced the speed advantage - the main benefit. And he offers caution regarding the faster data gathering methods, most latterly represented by the compound data gathering methods of Etalon and API. "People are looking for ways to collect data more quickly – quick's good, but accuracy counts, I believe Wyatt Earp is supposed to have said. With our equipment – XL80 laser interferometer – you measure one parameter at a time; with Etalon, API and other laser trackers, you make one run to collect multiple parameters.

Image: Using Renishaw's laser interferometer – XL-80 – measurements are gathered one at a time. Here the application is an Edel machining centre.

"We believe there are advantages in using a laser interferometer system. One, the traceability of the measurements is good; two, we do not believe the speed advantages cited for other systems are anything like what they are stated, in reality; third, by measuring one parameter at a time, it allows for a sanity check as each parameter is corrected for. If you collect a lot of data from various runs and input it all at once, and then find by running a check afterwards that there is still error, you can't pinpoint from where the error originates." Supporting the speed comment, *Machinery* was told by one industry expert that a large aerospace machine was measured for 21 errors in a single day, using Renishaw interferometer.

Basically, with the laser tracker type method, errors are being deduced by maths. And this maths approach varies, too. Indeed, maths is at the core of the recent development announced by machine tool maker MAG in the US.
Using API laser tracker technology, MAG (0121 306 5600) appears to have bettered the Etalon-based process, by offering a single set-up procedure to gather all the data for all linear and rotary axes (Etalon is a multiple set-up procedure).

US RESEARCH OUTPUT
The US development, announced in March, has resulted from a US research project, Volumetric Accuracy for Large Machine Tools (VALMT), involving API, Boeing, Siemens, MAG Cincinnati and various US Department of Defense (DOD) parties, under the auspices of the US National Center for Manufacturing Science. Siemens VCS is the control technology involved.

Image: The API laser tracker device being used on a large MAG machine. Single set-up is the key for the process, which employs a new maths approach developed by a Boeing employee to generate the individual error parameters to support Siemens' VCS, taking readings at a number of machine 'poses'.

The VALMT project had the machining of large, defence industry-related monolithic structures on machines with up to six axes (including robots) as its target, via an error measurement process that takes far less than the current "two to three weeks currently required", it is claimed. (Listen to an interview with MAG's Jim Dallam, product manager, volumetric error compensation (VEC) here (http://chilp.it/6eb402.) The VEC measurement process takes just a few days, he says, with repeat checks faster. (See a video of the process here).

At the core of the process is a measurement and data processing methodology that was developed by Boeing employee Phil Freeman for a PhD thesis (a related presentation is available here http://chilp.it/b3ae67). It was first applied within Boeing, then commercialised via the VALMT project. Using the API laser tracker and the reflector, an NC program is used to position the tool, in some 200-400 statistically randomised 5-axis "poses", with this run three times - once with a long tool and twice with a short tool length, explains Mr Dallam – the last run giving a measure for repeatability. The data is then mathematically processed by computer to generate the compensation tables for the Siemens CNC, with the program then run once more, with the compensations applied, to prove that there has been an improvement.

The VALMT project proved that the VEC process is suitable for wide application and that improvements in volumetric accuracy of "50 per cent or more" are achievable in days, not weeks. It can currently be used only with Siemens controls, but Mr Dallam offers that MAG and API are working towards a solution for Fanuc and other CNCs.

VEC is available on new and legacy MAG brand machines, assuming a viable machine and control in the latter case. Control requirements currently are Siemens 840D PowerLine CNCs at/after a specific release level, and/or Siemens 840D SolutionLine CNCs.

Siemens itself does not recommend any particular measurement methodology over another – it is for the machine tool builder to understand the differences and decide, it says. So its VCS will work with technology from Renishaw, Etalon, API and AfM (www.afm-tec.info).

Both Fanuc and Heidenhain are also working with Etalon, while Etalon itself has just announced a new development - on-the-fly collection of data (as opposed to the previous stop-start approach), with this speeding the data collection process further. This on-the-fly approach is already employed on Zeiss CMMs (Carl Zeiss, 01788 821770), and Siemens is also pursuing its application with Etalon.

In addition to technology development within CNC makers, machine tool makers and measurement technologists, this area is also drawing the attention of researchers. The UK's Huddersfield University's Centre for Precision Technologies (CPT), which has been active in this area for years, is involved in two European research projects - both incorporating real-time error measurement, as well as real-time compensation - while it is expected to unveil a development of its existing technology later this year.

The 'next big thing' or not, there is clearly increasing demand for the technology, which is driving the technology's development, so more applications will, no doubt, begin to surface over coming years.

Box item Links

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Box item 1

UK efforts have history
The UK's Huddersfield University has been working in this area and claims a number of installations. Its Centre for Precision Technologies' SinVCS system used to operate outside the CNC on a PC, intercepting encoder feedback, adjusting the signals by the required amount then passing them on to the CNC. This technology had proved effective in industrial applications for over a decade in 2004.

Further advances were made when the system was incorporated in an OSAI Series 10 controller via a DOS partition, then VCS was integrated within the Siemens 840D controller, running within the NC kernel itself - Siemens subsequently developed its own solution, VCS.

Huddersfield has a number of systems in place - at Micro Metalsmiths (see *Machinery* website here), BAE Systems, Rolls-Royce and GKN, and is continuing its development, specifically in reducing the cost of its technology - while it is also currently investigating use of Etalon technology to measure working volume errors.

Box item 2

Fanuc technology in action

For a 3-axis machining centre, a Fanuc RoboDrill, the effect when using Fanuc's volumetric error compensation on a machine having axis travels of 500, 400 and 330 mm in X, Y and Z, and taking 998 measurements at a pitch of 40 mm, was an increase in precision by a factor of four. The total calibration process, including assembly and modification, took only 90 minutes. Fanuc says that tests have shown that the positioning accuracy is improved on average by a factor of two. Multiple compensation tables for different temperature levels can be stored.

Image: Fanuc's error compensation technology in action on one of its own machines.

Box item 3

Doing the maths differently

There are public and well known maths to support compensation of the 21 errors of a 3-axis machine tool, this having been used for many years to support co-ordinate measuring machine (CMM) error maps. However, 5-axis volumetric error compensation requires additional maths and remains the subject of academic discussion. Most recently, the International MultiConference of Engineers and Computer Scientists 2010 saw a paper presented (Read the paper here). The paper "describes a new and simple analytical method to obtain the total volumetric (position and orientation) error at the tool throughout the workspace due to geometric errors of individual components on a 5-axis CNC machine tool".

Reflecting the variation in mathematic al approaches used by CNC makers, Heidenhain's Dr Kummetz says: "We have own [maths] libraries. The functional range allows for many different mathematical approaches to describe a certain machine kinematic. The widely used mathematical model for CMMs may be used as well."

Box item 4

Corrections outside the box

US-based Reichhold Machinery has for some time offered its Shadow Map software for 3- and 5-axis machine tools that reads industry standard APT CL machining programs and applies a correction to code before it is processed by the machine's CNC. Of course, measuring the machines volume was required to generate the error map.

Box item 5

Real-time error measurement and compensation – UK development

Huddersfield University's Centre for Precision Technology (CPT) is involved in two European research projects to push the boundaries on error compensation still further – ADAMOD (runs from October 2008 to 2011 for 36 months) and SOMMACT (runs from September 2009 for 36 months).

ADAMOD is focused on on-machine measurement, with a large reduction of machining errors caused by thermal effects (as measured in microns per unit volume), plus a reduction in machine vibration levels to improve surface finish. CPT's efforts here are focused on the former. It is currently employing so-called fibre Bragg grating sensors, as well as other sensors, on a machine model made of a material with similar properties to carbon fibre. Fibre Bragg gratings lengths are located on the machine structure and are sensitive to strain. It is envisaged that machine elements made out of carbon fibre will be employed in production machines in future.

Other partners in this project include Italian machine tool builder Fidia (project co-ordinator); Italian machine design and analysis specialist CeSI - Centro Studi Industriali; Spanish production technology group Fatronik; Germany's Fraunhofer-Institut für Silicatforschung (part of the Fraunhofer-Gesellschaft, Europe's largest application-oriented research organization); Belgian university Katholieke Universiteit Leuven; Italian vibration monitoring specialist SEQUOIA automation; Switzerland's SMARTEC, a sensor manufacturer.

SOMMACT's theme is also to reduce errors (by 75 per cent), but in this case via the use of an independent reference frame, separate from the machine structure's force loop, where machine structure movement with respect to this independent reference can be measured in real time and then compensated for. [UPDATE]The project will develop a "tool kit" that will combine not only separate reference frames but also sensors installed on moving machine components to gather essential information of geometric error functions induced by process disturbances like workpiece mass variation and ambient temperature variation.[END UPDATE]

Other partners in this are: Italy's Technology Transfer System Srl, a Industrial Innovation Consulting Services; [UPDATE] FIDIA spa, italian CNC and HSM machine tool manufacturer [END UPDATE]; Alesamonti srl, an Italian maker of large boring and milling machines; Italian regional business organisation API Varese; German precision machinist Havlat GmbH; Dutch precision measurement specialist IBS Precision Engineering; Italy's Istituto Nazionale di Ricerca Metrologica (National Institute of Metrological Research); [UPDATE]ISM 3D SL, Spain [END UPDATE]; machine tool maker KOVOSVIT MAS as, Czech Republic; German indexing table and part transport specialist Weiss GmbH; [UPDATE] and SUPSI, Switzerland will develop innovative self-learning and self-optimising systems [END UPDATE]

A key feature of both projects, according to Alan Myers, technical director Centre for Precision Technologies, is adaptive control in real time.

Incidentally, in all cases, each project partner retains the intellectual property for the knowledge/technology that it generates, so Huddersfield will be adding to its store of knowledge in this area, quite clearly.

Box item 6

Renishaw technology reveals errors

The Renishaw ballbar, introduced almost 20 years ago, was developed to offer a fast diagnostic check for CNC machines' linear axis performance. In conjunction with Renishaw software, it can identify up to 19 different errors, although these are not all the same as the 21 errors already noted in the main feature; some relate to dynamic errors, such as scale mis-match or backlash. These highlight whether there is, say, scale error, straightness error, or servo error, with this prompting use of a laser interferometer to check the first (with linear axis compensation file correction update following), mechanical adjustment in the case of the second, and the use of servo tuning software for the latter.

Image: Renishaw's ballbar being used on a Haas vertical machining centre.

The latest development, QC20, launched last November, offers a better approach to identifying volumetric errors by allowing a ballbar test in three different planes in a single set-up, versus the previously required three set-ups. Maximum travel of a ballbar is 100 mm radius as standard and up to over 1 m with extension bars. Once again, it is not a tool to support volumetric error compensation, but is a diagnostic tool.

Image: Renishaw's new ballbar development – QC20 – allows for tests in three lanes from a single set-up. Before, an individual set-up was required for each plane.

It reveals what the maximum error within the volume is, but not where it occurs. In trials with machine tool manufacturers, figures for errors "in the teens" have been witnessed, says Renishaw's Ralph Fergusson-Kelly, marketing manager for calibration products, but he offers that "until there is a better understanding of what representative figures are, people will be very cagey before making any claims in this area". And he adds that if you start to include uncertainties of measurements, with an increasing number of errors/measurements comes an increasing error budget, he advises. "If you took the worst-case figure in each variable, you would end up wondering how you make anything accurately, but in reality it tends not to be anywhere near that, in practice."

Renishaw also has technology to measure rotary axis error issues. Compatible with common formats of 5-axis and multi-tasking machines, the company's AxiSet Check-Up is said to offer machine users with a fast and accurate health check of rotary axis pivot points. Alignment and positioning performance checks are carried out rapidly to benchmark and monitor complex machines over time.

With its probing macro software and a dedicated calibration artefact, it provides graphical representations of multi-axis machine performance. It makes PASS or FAIL decisions, based on defined tolerances, and allows performance to be tracked over time, using history and comparison functions. All of which helps to identify poor machine alignments and geometry due to machine set-up, collisions or wear.

Performance analysis is reported graphically via Microsoft Excel, compared against user defined tolerances and stored for historical comparison. All results can be printed in a standardised report via Microsoft Word.

The company is also set to release AxiSet Calibrate for machine tool builders.

Box item 7

What's a good figure for volumetric accuracy?

Bristol-based Oldland CNC, is one of few companies that mentions volumetric accuracy in relation to its machine tools. The aerospace subcontractor installed a Hermle C 600 U vertical-spindle machine (Geo Kingsbury, 023 9258 0371) in 2006 and uses it for both 5-axis simultaneous and 3+2 positional 5-axis machining.

Image: Oldland CNC knows that it is volumetric errors that are important and that its Hermle machine represents a good example of one with a small error.

"The name of the game when producing high accuracy components, especially large ones, is not repeatability but volumetric accuracy of the machine tool' continues Tucker; 'manufacturers are often reluctant to disclose it, content to quote positional accuracy and repeatability in their catalogues," says managing director John Tucker, who observes also that Hermle doesn't quote such a figure.

"For all of our machine tools, we measure volumetric accuracy ourselves using a calibration ball and probe in the spindle. It is the only way to determine how accurate features in a component will be, relative to one another, if they are machined in diametrically opposite corners of the working area. When we checked the C 600 U, it had a total volumetric accuracy of 50 microns over the entire machining envelope, which I regard as excellent for a machine of this size moving in five axes," the managing director highlights for the 600 by 450 by 450 mm working envelope machine.

Box item 8

Siemens VCS supports thermal error compensation

Siemens' VCS supports multiple temperature-related compensation tables. Indeed, its VCS technology was used to support a recent European machine tool research project, NEXT in terms of temperature compensation (correcting 21 errors on a 3-axis MAG Powertrain Specht 500L horizontal machining centre), and Dr Bretschneider thinks that this application would be of interest for users of large machine tools and/or accurate machining processes, where reaction on temperature-caused machine accuracy change warm-up periods of hours are sometimes required.