VOLUMETRIC COMPENSATION FOR PRECISION MANUFACTURE THROUGH A STANDARD CNC CONTROLLER

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1 Introduction

Volumetric performance is replacing axis accuracy as the accepted measure of machine tool positioning performance. Long-term, multinational projects, such as the manufacture and maintenance of modern aircraft, require comparable machining performance for any machine used by any member of the supply chain throughout the world, for the duration of the project. Standards for measurement, such as ISO 230, and methods of evaluation of volumetric accuracy [1] are imperative in order to ensure each machine conforms to the required tight machining tolerances.

Having established a volumetric accuracy figure for a process, it is the responsibility of the machine tool builder to provide equipment capable of achieving the requisite accuracy throughout the volume. Misalignments, necessary clearances and imperfections during manufacture and assembly mean that a machine cannot be perfectly built, but error avoidance techniques [2] can be implemented to minimize the resultant error.

Good mechanical design and build practices should always be followed, with the limiting factor being the likely increased cost of implementing such a strategy. Compensation of the remaining errors can be a relatively inexpensive means of improving performance.

2 Volumetric compensation

Volumetric compensation has become an industry-accepted method of enhancing the performance of a machine. The principles have been applied for updating the numerical output of coordinate measuring machines (CMMs) to eliminate the inaccuracy of the machine from the measurement [3, 4]. A more complex problem is manipulating a machine to cause it to locate accurately. The error models are well known [5, 6] and compensation has been successfully applied on specialist equipment using a variety of methods [7]. However, devising a cost-effective solution that is readily applicable to a wide variety of machine types from different manufacturers provides an even greater challenge.

Different techniques of applying compensation have been attempted in both research and industry, with a major obstacle being the requirement of an efficient and cost-effective method of applying correction at a sufficiently high cycle rate. Any time-lag in the system would result in the wrong correction being applied, which could actually worsen the volumetric accuracy.

For example, a compensation system running in the PLC is limited by the PLC loop time. Compensation scheduled to be applied at a specific point might, in the worst case, not be applied for two cycles of the PLC. This means that, for cutting feeds of around 8m/min, there could be a delay of over 2mm before compensation is applied. At higher speeds (during rapid motion) of up to 100m/min, the error injection might not be achieved until the machine has moved over 20mm. If there are rapidly changing errors this will result in outdated correction values being applied – particularly problematic when compensating for errors caused by a rapidly moving servo head.

2.1 PC-based compensation

A hardware solution [8] is employed to apply correction at a sufficiently high rate. A PC intercepts position encoder feedback signals using special encoder cards. DOS-based compensation software then calculates the error in each axis direction at that point in space and issues commands to the cards to modify the pulse train to compensate this error.

The hardware required includes a PC, compensation cards, cabling, PLC interface signal cables and digital I/O boards. Each hardware element has an inherent cost and design cost and any required increase in functionality is likely to require a redesign of the hardware and communication protocol. The problems associated with retrofitting such a system are higher, since new cabling has to be routed, the PC has to be correctly and safely sited, PLC modification is required, etc. Furthermore, although installations of PC-based compensation have proved reliable, there remains the potential for faults to develop so a stock of spare parts must be maintained. While these obstacles are not insurmountable, they add complexity that would preferably be avoided.
2.2 Controller-based compensation

Implementing the same correction algorithms in a CNC controller offers a desirable solution as it eliminates the need for additional hardware. Furthermore, the system can become more versatile as the compensation software can be cognisant of all the active machine data and processes without the need for complex communication protocols.

Such a system has been implemented in the OSAI Series 10 controller [9] by running the compensation algorithms in a DOS partition and transferring an error-depndant offset to the NC to apply correction. This facility is not generally available in CNC controllers and a Windows™ partition cannot be utilised in the same way because of the processor overheads involved and the non-uniformity of operation that interrupts can induce.

This paper describes the application of the compensation algorithms through the Siemens 840D; a controller widely used for five-axis machining and throughout the aerospace industry.

2.3 Siemens 840D-based compensation

The Siemens 840D is an open-architecture controller that allows user cycles to be run not only in the Windows-based “front end”, but also as part of the NC process. This means that the compensation algorithms can be run as a compact program in real time as part of the NC cycle loop, avoiding problems of time delay or operating interrupts. At the same time, the Human-Machine Interface (HMI), designed in visual basic, has sophisticated yet user-friendly data input and diagnostic screens that have no impact upon the rate of application of compensation.

One consideration in embedding the compensation routines in the central NC processor was the effect this might have on the controller loop time. To avoid this, the system has been designed to act as a slave to the main controller cycles. In this way it uses the spare cycle time from the processor to apply compensation and does not cause interrupts to the main functionality of the Siemens kernel software.

A particular advantage of the system being resident in the controller is that it operates at the resolution of the controller because the software applies compensation in “internal increments”, which are one nanometre on the controller used for trialling. This means that compensation can be applied at this level, giving superior accuracy and surface finish results compared to a PC-based compensation system which is usually limited to a one micron resolution.

3 Results

3.1 Laser measurements

Compensation of the geometric errors of a machine is achieved by measuring each error using a laser interferometer or other metrology device. The error data is then input to the system and a compensation table is compiled and activated. The graphs in Figure 2 show the results of compensation for two such errors. The first plot shows the linear positioning error of one axis being reduced from 17µm to less than one. Such improvement should be possible from standard CNC compensation, although the spatial resolution using VCS generally produces better results. The second graph shows compensation for an axis straightness error. This component is more difficult to compensate as
it requires a stationary axis to overcome stiction and inertia to compensate the error in the travelling axis. Similar improvements were achieved despite the increased challenge.

Figure 2: Compensation of two geometric errors

Figure 3 shows the results achieved for all measured errors. For the squareness and angular errors, such as pitch (e.g. X about Y), roll (e.g. X about X) and yaw (e.g. X about Z) the figure presented is the maximum linear effect of the error experienced during motion of the axes. It is this value which influences the positioning capability of the tool tip.

The volumetric accuracy of the machine is the combination of the linear effects of each of the errors. This is calculated using software [1] which extrapolates the measured error information and estimates the positioning capability throughout the available working volume. This value was found to be 65µm for the uncompensated machine. This was reduced by 97% to 2µm after compensation was applied. Such a dramatic improvement brings the positioning capability of this standard-build machine tool to the same level as a high-accuracy CMM.

Figure 3: Compensation of all three-axis errors

3.2 Cutting trials

A validation of the measurement and evaluation strategy and the effect of compensation on a machined surface was conducted by machining a number of test pieces based upon the NAS-979 test. To provide quantitative results for comparison a high-accuracy CMM was used, among other things, to dimension the diamond circle and square. The designation and results (Figure 4) show that the machining errors were relatively small without compensation, due to the size of the workpiece and good condition of the machine. Nevertheless, compensation has been found to improve performance to the level of the uncertainty of measurements of the compensation data and of the dimensioning on the CMM.

An important feature of the cutting trials is that the location of the workpiece during machining differed from the region of the machine where the laser measurements were taken. This provides confidence that the manufacturing performance can be achieved throughout the entire volume, not just for the relatively small subset where compensation data was captured.
4 Conclusions

This paper describes the implementation of a volumetric compensation system in a standard Siemens 840D controller. This system can be applied to any three-axis machine tool and many five-axis configurations. The system requires no additional hardware, with downtime for integration being limited to that required for entering parameters and measurement data.

Compensation results from metrological testing have shown an improvement of 97% in the volumetric accuracy of the machine, giving a compensated value of 2µm, challenging the instrumentation used for measurement.

The system has been further validated by cutting trials. The results are subject to the geometric error of the machine, error due to tooling, dimensioning. Under these conditions, all errors were reduced to less than 5µm.

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References