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Contouring accuracy assessment of CNC machine tools - a user's view

M. Gull
AWE, Aldermaston, UK

Abstract

The purpose of this paper is to discuss the methods used at AWE Aldermaston to assess the contouring accuracy of computer numerically controlled (CNC) machine tools procured by AWE. It will also explain how the measurement and evaluation techniques have been developed over the years for this purpose.

Aldermaston has been involved with precision machine tools for the past thirty years, although mostly lathes, they have ranged from copying to the present day computer controlled machines. As a result, most of the techniques explained in this paper originated from the need to assess the contouring accuracy of lathes although the present techniques can be used just as effectively on CNC milling machines.

The importance of contouring assessment for CNC machine tools is now widely established by the work of Knapp [3] and Kakino 4] who proved that contouring profiles can be used to diagnose the various error components within the system. These can provide information on the geometry, control system and drive mechanisms as well as any thermal distortions between tool and workpiece zones.

No attempt will be made to describe in detail the various analysis techniques used to evaluate contouring assessment as that is now widely documented. Equally, only those test methods actually used at AWE will be discussed.

Introduction

Accuracy, defined as a ' Measure of degree of conformance to recognised international or national standards' [1] is a general term and refers to the conformance to specification of different attributes of an artifact. In our case, this is a machine tool or more specifically the elements of a machine tool that govern contouring capability.

The purpose of this paper is to discuss the methods used at AWE Aldermaston to assess contouring accuracy of machine tools and how these measurement and evaluation techniques have been developed over the years. It will also address the subject of standards, both national and international, and how they have attempted to keep pace with these methods.

Currently we are in the middle of a technological revolution in machines, which is generating an urgent need to produce components as accurately and economically as possible, often coupled with the requirement to eliminate the skilled operator with his 'feel' for, and constant correction of the process. In 1982, Taniguchi [2] characterised this increasing dimensional accuracy capability of metal cutting machine tools and other processes over the years and predicted the achievable accuracy for the future.

Aldermaston has been involved with precision machine tools for the past thirty years, although mostly lathes, they have ranged from copying to numerically controlled (NC) to computer controlled machines (CNC) through to the latest ultra precision diamond turning lathes. As a result, most of the techniques explained in this paper originated from the need to assess the contouring accuracy of lathes.

The importance of contouring assessment for CNC machine tools is now widely established by the work of Knapp[3] and Kakino[4] who demonstrated that contouring profiles could be used to diagnose the various error components within the machine's system. When a machine tool performs a circular interpolation, its position, velocity and acceleration are constantly changing in two or more axes. Its capability to execute a circle (or partial circle) can be influenced by many possible sources of error which combine to make a performance fingerprint unique to that machine. Diagnosis of the circular plot can highlight the roots of individual problems such as information on the machine tool's geometry, control system and drive mechanisms as well as any thermal distortions between tool and workpiece zones.

MEASURING METHODS

Machine tools are manufactured to the highest degree of accuracy and precision commensurate with their cost, but inevitably there must be a compromise between price, quality and their dynamic characteristics. Aldermaston operates a procurement policy where all machine tools are inspected at manufacturers works prior to delivery and then again after commissioning. These acceptance tests include a combination of parametric checks, where the various geometric elements of error are measured individually followed by functional checks where the machine's overall accuracy capability is measured.

This policy is based on the understanding that the accuracy of a machine tool is a complex combination of parameters which influence the accuracy of the machined workpieces. Experience has shown that upon delivery, the initial calibration could have changed and after a sufficient settling in period most will change again and require a further recalibration. Previous research [3,5] suggests that the primary factor that influences machining accuracy is the motion accuracy of the machine tool. When

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there is a motion error in a machine tool, it will be transferred to the profile of a machined component and could result in high component failure rates. In order to define the machining accuracy, the relationship between errors of the workpiece and the errors of the machine (both static and dynamic) need to be understood.

Assessment of the contouring accuracy of a CNC machine tool starts to address this relationship by combining most of the factors, with the exception of the 'load' generating elements such as the workholding and tool holding spindles.

Assessment involves two basic methods; indirect and direct. The indirect method uses some form of instrumentation in conjunction with artefacts for the assessment and evaluation of the geometry and control system over the working volume of the machine. The direct method relies on the machining of a specific component or test piece followed by it's detailed and careful evaluation off-line.

INDIRECT METHODS

Complementary to such 'absolute' tests as laser and optical calibration procedures, are a range of indirect methods using no-load artifact-based assessment procedures ranging from circularity tests using a circular reference disc to telescoping and fixed length ball bars.

This section discusses the continual development of one particular indirect system, used at AWE, from it's roots in hydraulic copying lathes through to its use on a ultra-precision diamond turning centre.

Twin Disc Checks

The concept of using no-load instrumentation tests to assess a machine tool's contouring capability instead of cutting test pieces is not particularly new. In 1958 the Lawrence Livermore National Laboratory in the United States developed a method of assessing the contouring accuracy on copy lathes. This method was termed the 'Twin Disc Check' (see Fig. 1) and was introduced to AWE around the same time.

The twin disc check measured the overall accuracy of the lathe's copying system as well as the lathe axes which reproduced the template shape at the tool. Templates of any size could be used, provided that both templates were identical.

To carry out the test, one disc was mounted on the lathe template carrier and the other positioned

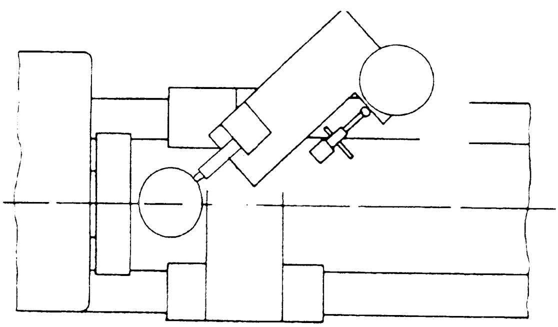

Fig 1 Twin Disc Setup

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near the spindle nose, on the centre height of the lathe. A sensing probe, having the same radius as the copying stylus, was mounted in the toolpost and positioned at the pole of the work disc. The discs were adjusted until they were in the same position relative to the sensing probe and stylus, this being carried out by successive adjustments to the twin discs, until the pole and equator readings are identical. A strip chart recorder was used to record the output from the probes and correct interpretation of the results demanded a thorough understanding of potential error sources as well as a knowledge of copying procedures.

Single Disc Checks

As numerical controlled lathes (NC lathes) began to make their mark in the workshop, so the need to use the second 'template' disc disappeared. This new technique therefore evolved and became known as the Single Disc Check or Master Part Trace Test and was designed to investigate the overall performance of the slideway positioning systems under numerical control (see fig.2).

A disc of known diameter and roundness was mounted on the machine bed so that the edge of the diameter coincided with the plane of the cutting tool, and in the position in which the workpiece would occupy.

A sensitive, single axis, displacement probe was mounted in the toolholder in place of the tool at an angle of 45 degrees to spindle axis. The lathe was programmed with the same radius as the disc, and set to follow a tool path of 100 degrees, (90 degrees plus 5 degrees at both extremes). The object of the extra 5 degrees at each end of the quadrant was to evaluate the slideway reversal points.

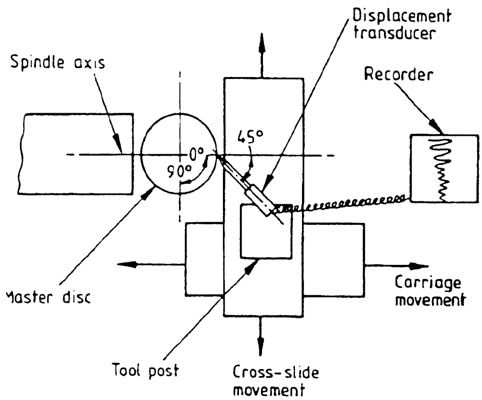

Fig 2 Single Disc Schematic

The probe was then set to zero at both the equator and pole of the disc, then reset to a start position which coincided with the datum start on the control programme. Once the numerical controller was started the probe would follow the contour of the disc, and any departure from the true form would show as errors on the probe output. This was recorded on a strip chart recorder and provided a permanent record of the machine performance.

The resultant straightline trace gave a contour accuracy assessment under no-load dynamic conditions, usually accepted as the 'best contouring accuracy' obtainable.

Unlike a cutting test, this instrumentation test was analysed on a statistical basis using a number of repeat runs from differing directions of travel and

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feedrates. The operating conditions were changed after each test to establish the optimum contouring accuracy of the machine. All this was achieved in situ with the time required to assess each change kept to a minimum.

The importance of this check cannot be overemphasised, as it served to check both the overall dynamic performance of the slideway and the numerical control system. Closely approximating an actual machining operation, it neglected only cutting forces, tool wear, and the thermal effects of a rotating spindle. The only disadvantages of this system was, owing to the fixed orientation of the probe, the measurements were restricted to a maximum partial arcs of approximately 100 degrees. This has to a certain extent restricted its use to lathes. In addition the start and stop positions, where the probes were set to zero, coincided with the points of maximum side loading and thus error, for the probe. This error could be greatly reduced by the use of a single axis flexure probe holder which allowed axial movement but was extremely stiff to side loads. Various performance validations were carried out by AWE's Metrology Laboratory which showed that the dynamic measurement uncertainty of this system was in the order of +/- 0.012 mm.

This technique was incorporated within the BS 4656 series of machine tool testing standards in 1988 (BS 4656:Part 28 'Specification for Numerically Controlled Turning Machines' refers).

Ball Bar

With the development at AWE, fifteen years ago, of a new range of high precision lathes that had a contouring accuracy specification of +/- 0.005mm, a requirement was identified for an improved measuring capability to exceed the contouring accuracy of these machines. As a consequence, a development program was instigated to develop a new high accuracy no-load contouring accuracy measurement system.

At that time, work had just started in the UK by Burdekin [6] and at the Lawrence Livermore National Laboratory in the United States by Bryan [7] on a different approach to contouring assessment using a ball bar design (see Fig.3) which exploited the advantages of a kinematic link and single axis displacement probes. With both these techniques the problems of manufacturing the high precision 'master' disc, setting the calibrated disc up on the machine, as well as the physical limitations of the 100^0 measurement arc were all overcome.

After evaluating both systems, and because there were no commercial systems available, it was decided to

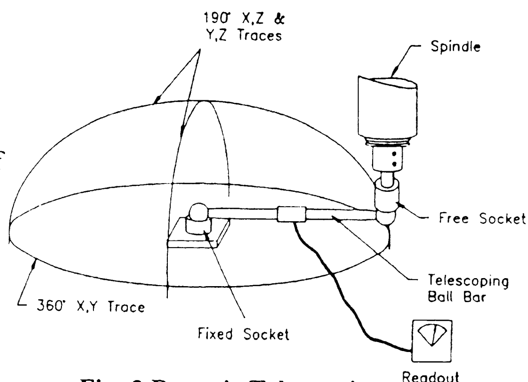

Fig. 3 Bryan's Telescoping Ball-bar

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engage in a joint programme with Burdekin to develop his system. This system, called Contisure (see fig.4), was a computer aided ball bar system for the measurement and analysis of radial deviations from a programmed circular profile. Since Contisure was developed, the concept of verifying a machine's contouring accuracy by the use of ball bars has resulted in a number of commercial systems such as the Renishaw 'Quick Check' and 'QC10' appearing in the market place. The Quick Check was released in 1992 and was a 150 mm ballbar incorporating a conventional displacement sensor, it also used a patented magnetic cup system for locating the ball bar onto the machine to be tested. The QC 10 ballbar system followed in 1993 and used a Zerodur™ length calibrator to accurately calibrate the ballbar length and a novel, laser mapped, inductive sensor for improved system accuracy. Both the Quick Check and the QC 10 systems were purchased in 1993 by AWE.

The Contisure system comprised two high precision reference spheres, rigidly mounted at the tool and workpiece positions. A transducer link of carbon fibre construction and containing two single axis displacement transducers, were located kinematically between the two reference spheres. These two transducers contacted directly onto the two spheres and the summation of their outputs represented the change in the centre distance of the two reference spheres. The absolute distance between the two spheres was established by setting the transducer link against a calibrated setting block manufactured from a low temperature coefficient material called Invar™. The voltage output from the probes was fed to an analogue display and thence to an A/D interface card which converted this output to a digital signal that was processed and displayed by a computer.

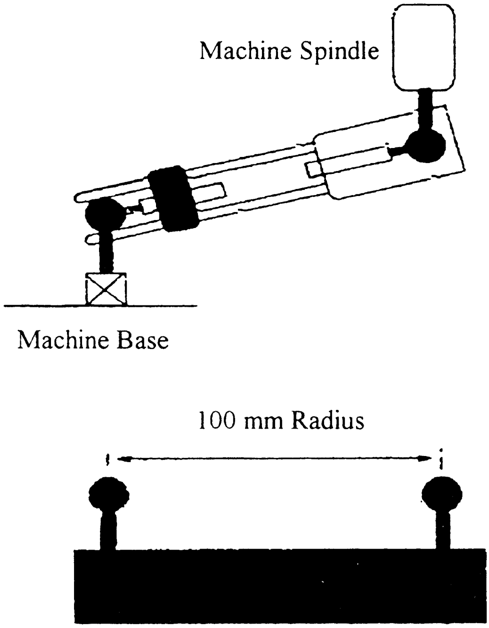

Fig.4 Ball Bar Link and Setting Block

Thermal Effects Thermally induced errors compare in size and type to those that result from geometric and control system deviations. They also include components not directly related to the machine such as room temperature and lighting. As the ball bar is set to a predetermined length on the setting gauge it was imperative that its length should also be adjusted for temperature.

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The setting block was initially manufactured from cast iron so that its temperature coefficient would be similar to that of most machine tools. Two temperature readings were then taken after a suitable settlement period; one from the machine under test and the second from the setting block. In theory these should have been similar but in practice were generally different, most probably due to the different thermal masses of the machine and setting block. To overcome this slight problem, a second setting block was manufactured from Invar™, which has a coefficient of 1.2 parts per million/ degree C. After each measurement run the link was returned to the setting block to be checked for both electronic and temperature drift.

In 1994, research was undertaken at AWE to evaluate the static errors that could affect ball bar accuracies during their usage. It found that the most significant test in terms of error magnitude was found to be the thermal response of the ball bar due to handling prior to data acquisition. In practice, the procedure involved during this pre-measurement phase was unavoidable and could increase the measurement uncertainty of the ball bar by as much as 0.010 mm. However, these errors could easily be reduced by careful handling and temperature stabilisation, and most of the ball bar manufacturers now advise users of this potential problem. The result of this work was published at the 31st International MATADOR Conference [8] in 1995.

Data Analysis Using ball bar systems, a comprehensive and rapid check of the geometry for the CNC lathes and the diagnosis of the contour motion error source can be determined by analysis of the resultant error plots. In its basic form the results can be used as a 'footprint' or reference so that the machine's contouring accuracy can be monitored over the medium and long term.

In it's more analytical form, position dependent error parameters such as angular motion (pitch and yaw), perpendicularity and dynamic positioning accuracy of each axis can be assessed. Positioning errors can be separated from the angular errors by carrying out two position tests in each axis. The pure angular errors can be obtained, only if the errors are linear, by subtracting the results obtained from two different radius contour tests.

In addition the system can be used as a quick check of the CNC servo systems leading to the adjustment of machine parameters of the numerical control and drives. By changing the contouring speed, the circular deviation can be determined depending on the speed and acceleration of a single machine axis. From the results of these tests, the maximum possible speed and acceleration can be established to enable the contouring accuracy to be within the specified tolerance. Other feed motion dependent errors such as the mismatching of the position loop gains, interpolation, hysteresis, vibration and errors due to servo response are easily analysed from the error.

Standards At International level, a new standard published by ISO provides a method for the measurement of the contouring performance of NC machine tools, titled ISO 230-4 "Acceptance Code for Machine Tools - Part 4 Circular Tests for Numerically Controlled Machine Tools". It specifies methods of

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testing and evaluating the three main deviations resulting from a prescribed circular tool path that are produced by the simultaneous movement of two linear axes. This standard brings together all the previous work on contouring assessment using either ball bars or calibrated discs and sets out standard test methods and data analysis as well as a standard format for presenting the data.

Nano-Master Template

In 1993, AWE began acceptance test procedures on a three axis ultra precision lathe. The three axes being X, Z and B, where B was a rotary axis that carried the tool holder. The test method described here was developed jointly by AWE and Cranfield Precision Engineering Ltd., (who designed and built the machine) and utilised all AWE's previous contouring experience.

The object was to determine the machines tool path accuracy to a tolerance of +/- 125 nanometres whilst the machine axes described a full 360° path involving linear motions of X and Z axes and rotational motion of the B axis. Throughout the circular move, the tool position was maintained normal to the circular path by the B axis.

A 150 mm diameter Invar™ ring gauge was mounted horizontally from the spindle housing so that its centre line was on spindle axis. A high accuracy capacitance probe (10 nanometre resolution) was mounted onto a fixture holding an XY stage that was fixed to the B axis in such a way that the probe tip was on the spindle axis of the B axis (see fig. 5).

Once the test setup was completed and both thermally and mechanically stabilised, a drift check was performed to establish it's sensitivity towards environmental changes and 'electronic' noise. Results of this test showed a static error band of 123 nanometres mainly due to the effects of 'electrical noise' and as a consequence it was decided to apply a low frequency filter to the actual measurement runs in order that this effect could be minimised.

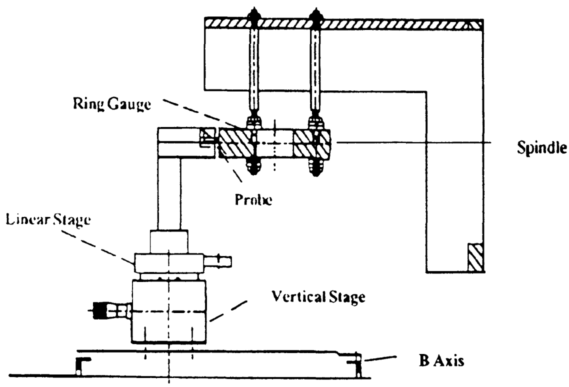

Fig.5 Schematic of Contouring Accuracy Setup

Two measurement runs were carried out based on the Reversal Technique, asdetailed below, in order to eliminate the ring gauge errors from the data.

Firstly the machine was programmed to move the probe around the ring gauge in a clockwise direction at a radius equal to that of the gauge at a feedrate of 0.1 mm/sec. A data logger, whose start and stop points were determined by an optical switch, was set to record radial deviations between the

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machine's position and the ring gauge profile. Then the gauge and probe were rotated through 180° by using a precision polygon, mounted above the ring gauge, and auto-collimator. A second set of data was then recorded with the same machine movements. Machine errors were seen as positive in the first measurement and negative in the second whilst the gauge errors remain unchanged. Subtracting the second set of measurements from the first set gave a value equal to twice the machine error. Using this technique gave a contouring accuracy of +/- 94 nanometres on the 150 mm diameter ring gauge,(fig.6). This test, part of a complete series of acceptance tests was reported in more detail at the LAMDAMAP 95 Conference.[9]

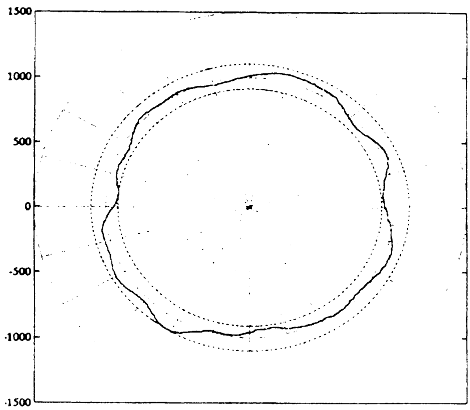

Fig.6 Final Contouring Accuracy

DIRECT METHODS

Machining tests have much in their favour since they reveal those parameters such as dimensional accuracy and surface finish which are of direct consequence to the user. However, using a machining test alone to determine contouring accuracy is not generally recommended. There are many variables that can affect the test part in a machining test that have no direct relation to the machine tool, for example material properties, tool wear, coolant flow and selection, temperature fluctuations and programming errors.

After machining the test piece, it is necessary to measure it's accuracy and this is usually inspected on a coordinate measuring machine, a roundness measuring machine and a surface finish measuring machine. This process is quite time consuming and could introduce additional measurement uncertainties into the test piece from the measuring equipment and technique. Even if the measurements were accurate it could still be difficult to accurately analyse the measurement data to match error profiles to machine elements.

The cutting tests are classified as either standard-type tests, which are formulated by large companies and institutions, (ref. BS 4656:Parts 28 & 30) or as non-standard-type tests which usually take the form of customer workpieces.

Non-Standard Type Test Pieces

Machine tool customers may, as part of an acceptance test, specify the machining of one or more of their particular components. Although such a test

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may cover only part of the machine capacity, the particular component used for the cutting test may have played a significant part in the original justification for the purchase of the machine. For the customer, this gives the added benefit of seeing the machine cope with his particular machining requirements as well as generating the NC program and checking the tooling.

Customer oriented cutting tests may not be that easy to verify unless accurate measuring machines are available, often this is done at the customers site which in itself can create problems if there is any dispute over the results. In addition, the error in the parts could be caused by factors outside the control of the machine manufacturer. For example, clamping distortion, material stress release and tool wear effects, along with component stiffness could be significant factors in determining the resulting accuracy of the component type test.

Standard Type Test Pieces

These have been devised, usually in conjunction with parametric tests, to show the relationship between measured errors and machine errors. Thus the test piece shape is chosen, not to represent a typical product, but to highlight the maximum amount of detail regarding actual machine errors. The main criteria in selecting the shape of the standard type test piece are as follows:

a) Maximum verification of contouring accuracy
b) Simplicity of programming
c) Ease of measurement

The material cost of these test pieces can be relatively high and, unlike customer component test pieces, they have only scrap metal value after completion. To offset this, they do use standard programmes, fixturing and measuring techniques and they can be re-used to a considerable extent.

At AWE, we use two basic shapes, the first is the hemisphere for use on lathes and the second is based on the NAS 979 'circle on a square' test piece for CNC milling machines.

Hemisphere These are usually carried out in conjunction with a ball bar test and use an aluminium test piece with a included angle of 105 degrees, see fig 7.

Hemispherical test pieces provide a severe test for any type of lathe from copying to CNC. On the copy lathe, the slide velocity varies during cutting and the stylus is exposed to axial and side loading errors. In addition, with a twin feed copier, the motion of the copying slide will be reversed at 45

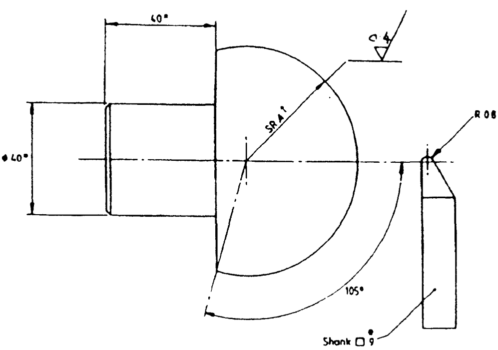

Fig. 7 Hemisphere test piece

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degrees and therefore changeover errors in the servo will be apparent. At AWE, typical form errors of +/- 0.004 mm on 100 mm radii hemisheres illustrate what can be achieved if close attention is paid to each possible source of error.

On the CNC lathe we see the same contouring errors induced by both geometric elements and slide velocity variation but in addition there are also the control system and drive errors . Generally the tool profiles are ground to the same accuracy as those for copying to minimise application errors.

The generation of the profile is by two methods; one uses only one block of NC programme to generate the 105 degrees, the other uses 7 blocks (every 15 degrees) to produce the profile. The second method is to check the dynamic transition of the NC blocks, a positive witness at points of transition would indicate the form characteristics of a multi-block contour. The test piece is checked for: deviations from programmed radius, measurement of the diameter, circularity and surface texture.

NAS 979 This normally features a 300mm circle on a 300mm aluminium oblique square. Thus the contouring accuracy can be established with the aid of a roundness checking instrument, where the effects of lost motion and interpolation errors can be readily shown.

The widely adopted practice of measuring the circle is by the use of a CMM to collect a number of points around the circumference in order to calculate its diameter. The number of points collected, although not affecting the diameter, will greatly determine the extent to which contouring errors are detected. Certainly extra care should be concentrated on the reversal positions (0, 90, 180 and 270 degrees) to examine for lost motion, etc. If any doubts exist concerning these positions then it is advisable to use a roundness measuring machine to fully sweep the circle.

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