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INTERNATIONAL STANDARDISATION -MOVES TO COMPLETE THE MACHINE CALIBRATION PACKAGE

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ABSTRACT

Standards concerning the determination of positioning accuracy and repeatability of numerically controlled(NC) machine tools have been published relentlessly over the last 20 years. Since the publication in 1988 of the International Standard 230-2 there has been a pronounced move, both at national and international standards level, to embrace further test procedures for a complete machine tool performance assessment. For example, measurements of angular (pitch, roll, and yaw) and straightness errors along linear axes are now commonplace and complement the existing positioning accuracy and repeatablity tests. More recently the subject of circularity evaluation has also gained considerable interest. Here dynamic tests, using a kinematic ballbar or circular masterpiece, give an instant overview of the contouring ability of the machine in two axes at specific feedrates. This information is extremely important in optimising machining accuracy.

This paper describes moves to complete the machine calibration package in national and international standardisation for the assessment of machine tool performance.

1. BACKGROUND

The performance of machine tools, particularly in relation to their positioning accuracy and repeatability characteristics, has been the subject of many national and international standards over the last 20 years.

The NMTBA standard[1] in the United States appeared in 1972 followed by the German VDI/DGQ 3441 standard[2] in 1977. In 1985 the British Standard BS4656 : Part 16[3] was first published giving three statements of machine acceptance, namely; mean reversal value, repeatability and accuracy. However in 1987 the British Standard was amended to include four definitive statements with unidirectional repeatability and bidirectional repeatablity being quoted separately. Then came the International Standard ISO 230-2 [4] in 1988 which was essentially similar in content to BS4656 : Part 16 : 1985.

Into the 1990's British Standard Technical Committee was formed to revise the accuracy and repeatability standard in line with current thinking from both UK machine tool manufacturers and users. This resulted in the publication of BS3800 : Part 2 : 1991[5] entitled "Statistical Methods for the Determination of Accuracy and Repeatability of Machine Tools"

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and is included in the BS3800 series of standards which deal with "General Tests for Machine Tools".

In 1990 the working group ISO/TC39/SC2/WG2 was also formed to revise the existing International Standard. There are at present two parts to ISO 230, namely a code of practice for testing the geometric accuracy of machines, and statistical test methods for the determination of accuracy and repeatability of machine tools. ISO 230 : Part 1[6] is similar to BS3800 : Part 1 : 1990[7] and contains a code of practice for testing geometric accuracy of machines operating under no load or finishing conditions. It gives various geometric and practical test methods including descriptions of measurements of straightness, flatness, parallelism, squareness and rotation. Definitions of these measurements are also included along with definitions of circularity and cylindricity. The use of checking instruments, explanation of tolerances and a description of the accuracy of the instruments required is also given.

The current revision of ISO 230-2 outlines statistical methods for the determination of accuracy and repeatability by direct measurement of independent axes on the machine. The standard may be used for type testing, acceptance tests, comparison testing, periodic verification and recalibration of machine tools.

2. POSITIONING ACCURACY

Test conditions both for the environment in which the machine is located and for the machine itself are given in the standard. It states that where the temperature of the environment can be controlled it shall be set to 20℃. However any temperature difference from 20℃ can cause an additional uncertainty of approximately ± 2 μm/m℃ and this should be considered. The machine under test should be completely assembled and fully operational with all levelling and functional checks having been completed. The tests are performed with the machine in an unloaded condition (ie. with a workpiece) and measurements are usually taken between the workpiece and tool positions after an appropriate warm-up period.

If the test equipment used includes a laser interferometer then for measurement of positioning accuracy environmental compensation for air temperature, pressure, relative humidity and machine temperature shall be used to yield results correct to 20℃.

To assess positioning accuracy and repeatability the machine is programmed to move the moving part along the axis under test and is positioned at a series of random target positions along the length of the axis. The selection of random positions means that cyclic errors will also be properly detected.

For machine axes up to 2 metres in length an overall minimum of five target positions and an overall maximum of twenty-one target positions may be selected and each target is approached five times in each direction, ie. five bidirectional measurement runs.

For axes longer than 2 metres, one bidirectional measurement run is performed and target positions are selected on each element of the measuring transducer or at 250 mm intervals where the measuring system is continuous. A 2 metre length of axis is also selected in the normal working region and an accuracy and repeatability check over five bidirectional measurement runs is performed.

Statistical analysis then takes place which assumes a Gaussian distribution. The mean positioning error, standard deviation, and the ± 3 sigma repeatability bands are then calculated and the following definitive statements of machine acceptance may be recorded :

☐ Mean Positioning Deviation

The mean positioning deviation calculated over all target positions.

□ Mean Positioning Reversal Error
The average value of the differences between the positional deviations in the positive and negative approaches at each point along the axis.

□ Unidirectional Positioning Repeatability
The maximum value of the range between the mean positional error plus 3 sigma and mean positional error minus 3 sigma, at any target point, in either the positive or negative approach.

□ Bidirectional Positioning Repeatability
The maximum value of the range equal to the 3 sigma band(+ve approach) plus the 3 sigma band(-ve approach) plus the reversal value; (6s) max (+ve); or (6s) max (-ve) at any target position along the axis.

□ Total Positioning Accuracy of an Axis
The maximum difference between the extreme values of the mean positional error plus 3 sigma and the mean positional error minus 3 sigma over all targets regardless of the direction of motion.

Machine tools acceptance and then be verified by comparison of these definitive statements with the machine tool manufacturers performance specification. These statements give most of the information required in passing off the accuracy of an axis; from backlash and positioning errors, through repeatability calculated for both unidirectional and bidirectional approaches, and finally a total positioning accuracy statements incorporating all errors; ie. reversal, positioning, and non-repeatability(Figure 1).

Positioning accuracy is normally stated over the entire length of the axis, however if

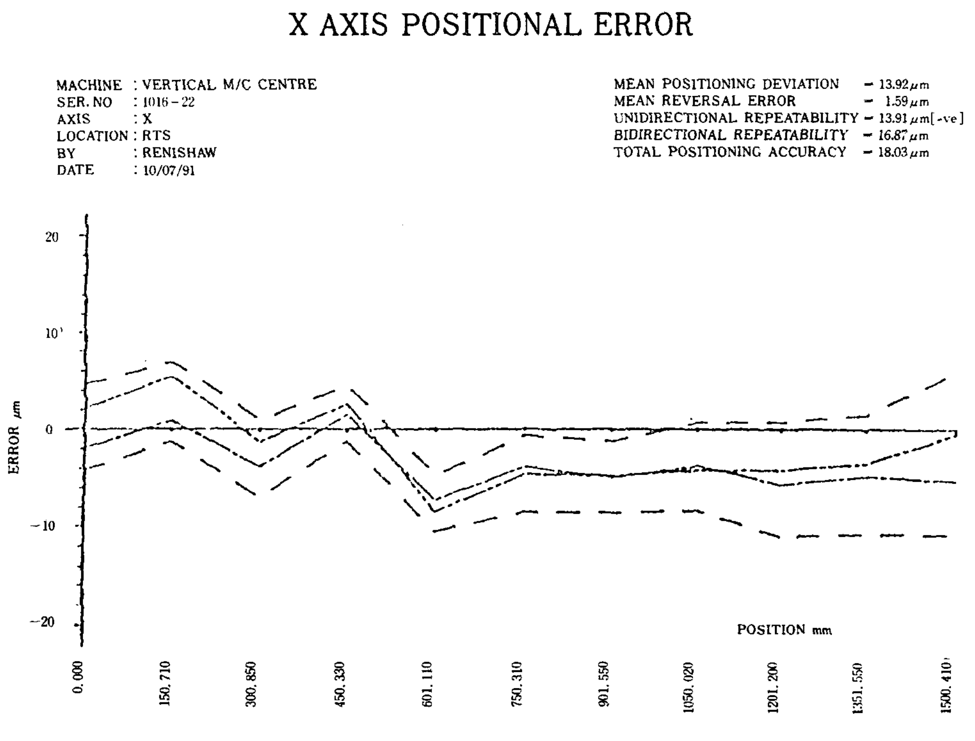

Fig. 1 Positioning Accuracy-Analysis to ISO 230-2

required the principal parameters shall be specified over a working length of 300 mm also.

3. ANGULAR (PITCH, ROLL, AND YAW) AND STRAIGHTNESS ACCURACY

The newly published British Standard BS3800 : Part 2 : 1991 also included statistical methods for the determination of angular and straightness accuracy[8]. Although this information is of great importance to the machine tool builder and user it is only recently that these methods have been embodied in national standards.

Unlike the measurement of positioning accuracy, measurement of angular and straightness accuracy applies to both numerically controlled (NC) and manually operated machine tools while basic machine structures, beds and slideways may also be assessed.

The machine is again programmed to move the moving part along the axis under test and is positioned at a series of target positions. These targets may be of uniform spacing or a random series and measurements are performed according to the linear cycle. Alternatively a constant feedrate may be set over a specified distance and the deviations may be recorded at fixed intervals as the moving part moves along the axis.

A minimum of five target positions per metre should be selected along the axis, although ten to fifteen positions will give more detailed information and five bidirectional measurement runs are performed. For measurements of straightness a regression line is fitted to the measured data values using least squares analysis.

In presenting the results of angular and straightness measurements the following definitive statements of machine acceptance may be recorded :

- ☐ Mean angular deviation
- ☐ Mean angular reversal error
- ☐ Unidirectional angular repeatability
- ☐ Bidirectional angular repeatability
- ☐ Total angular accuracy
- ☐ Mean straightness deviation from the regression line
- ☐ Mean straightness reversal error
- ☐ Unidirectional straightness repeatability
- ☐ Bidirectional straightness repeatability
- ☐ Total straightness accuracy

Machine tool acceptance may again be verified by comparison with the manufacturers performance specification and values of angular and straightness errors may also be compared with the relevant machine specification in the international standard or in the BS4656 series of standards[9] relating to machine type (Figure 2).

With some measuring systems, however, there may be some non-repeatability during the acquisition of angular and straightness data. The "uncertainty of measurement" is affected by the resolution attainable with the measuring system and random fluctuations, for example air turbulence. A test of the uncertainty of measurement along a machine axis determines the spread of results of repeated measurements which is wholly attributable to the measuring system and represents the ability of the measuring system to reproduce the value of a physically unchanging quantity when a measurement is carried out a number of times.

This test involves programming the machine to move to a target position and recording a number of successive measurements equal to the number of measurement runs used in the straightness or angular tests; these measurements being taken with the machine axis stationary. The test may be carried out at both the first and last target positions along the axis. If the uncertainty of measurement or scatter in the above test is greater than one-

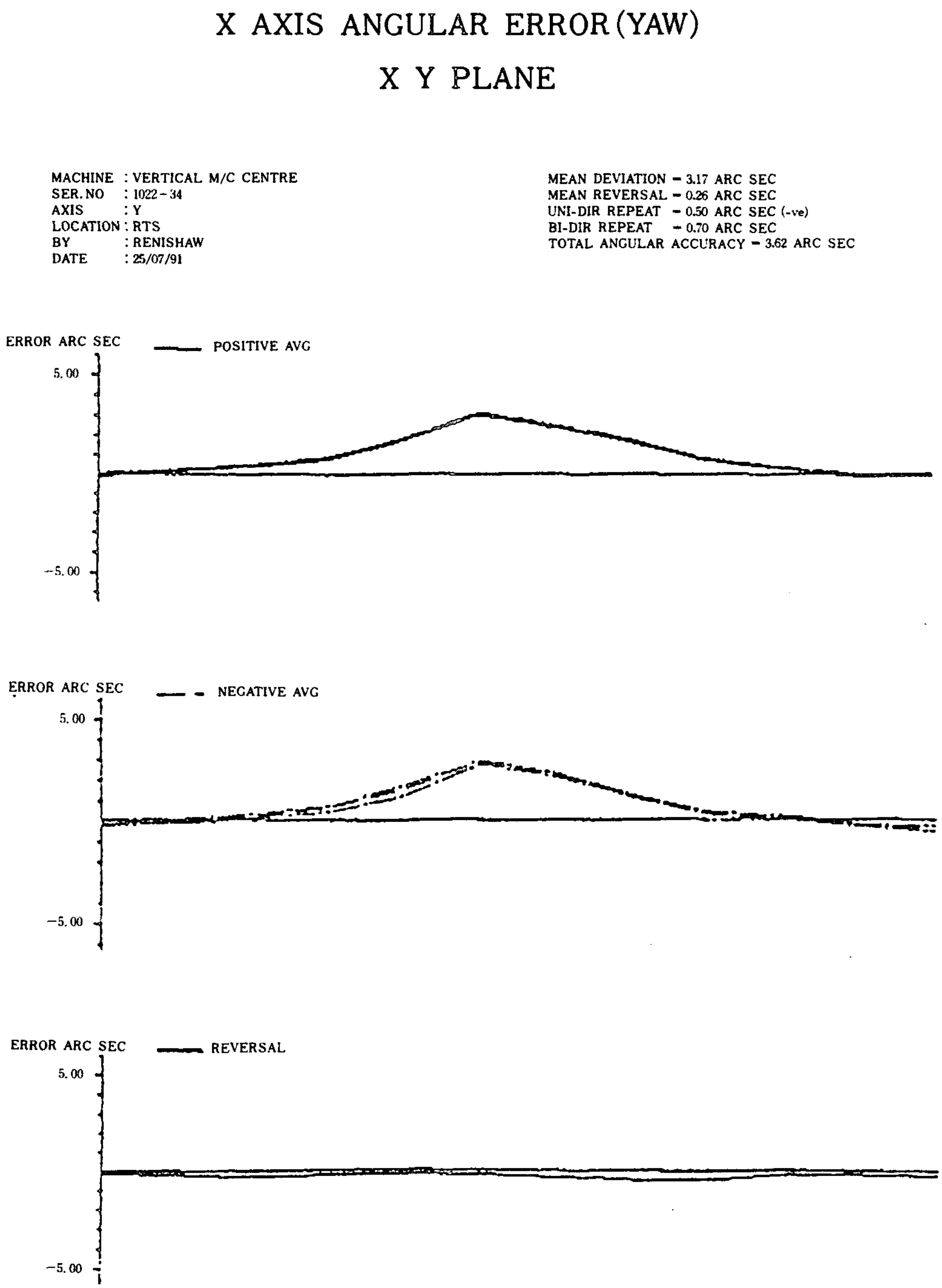

Fig. 2 Angular Errors (YAW)-Analysis to BS3800 : Part 2 : 1991

third of the unidirectional repeatability recorded in the standard test then no repeatability figures are quoted or plotted for the axis and no total angular or straightness stated. Therefore statements of mean deviation and mean reversal along with the uncertainey of measurement figure would only be given (Figure 3).

4. CIRCULARITY

Together with the calibration of individual machine axes further evaluation of machine tool performance may be gained by dynamic measurement which more closely represents the machining operation. One method of checking a machine to ensure it is reading correctly is to cut a test piece and then check its machining accuracy using a coordinate measuring machine. This is obviously a time consuming exercise and many test pieces may have to be machined before completely optimising the major machine parameters.

An alternative and much quicker method is to examine the machine by performing a circular test, a comparison of a circular path[10]. This involves the simultaneous movement of two lin-

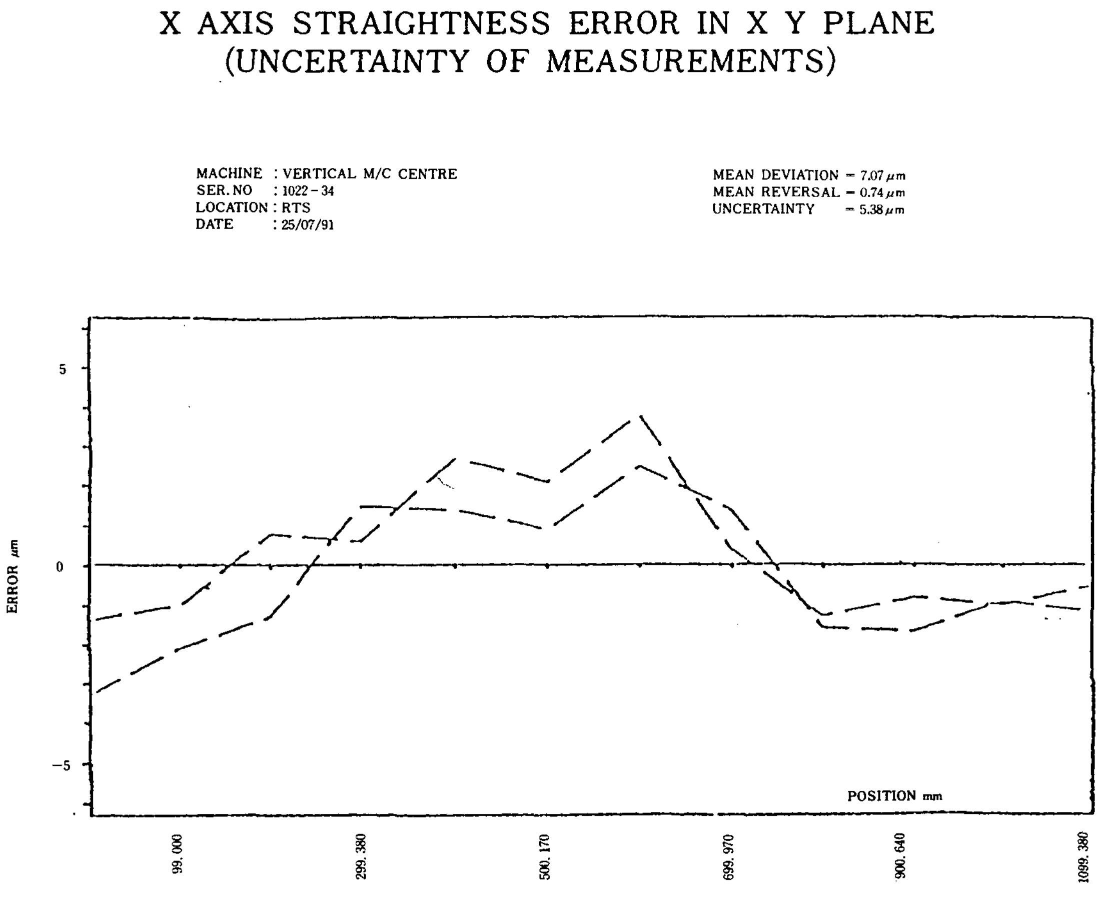

Fig. 3 Straightness Error-Analysis to BS3800 : Part 2 : 1991

ear and normally perpendicular axes whose combined movements scribe a circle. Programming is straightforward on most CNC machines and circular tests can reveal problems and inaccuracies in the numerical control, drive servos and the machine's axes.

Measurements of circularity can be carried out according to the definition contained in ISO 230-1 where it states that : a line situated in plane is said to be circular when all its points are contained between two concentric circles whose radial separation does not exceed a given value.

A new ISO working group, ISO/TC39/SC2/WG5 was recently formed to produce a general method of test for the measurement of circularity thus confirming the great interest worldwide shown in the this subject. Test equipment which may be used to measure circularity of machine axes range from a rotating one dimensional probe and test mandrel to the more sophisticated circular masterpiece and bidirectional probe, or kinematic ballbar.

To assess circularity a test radius of the nominal path, contouring feedrate and sense of contouring, either clockwise or counter clockwise, are selected. Two axes are then programmed to produce the actual path and data may be capured through 360° or around a partial arc, ie less than 360°. Using a dynamic data data capture facility for example the position of the machine axes and subsequent circularity error may be recorded up to 3600 points around the measurement path. The main aspect of dynamic data capture is that data is captured automatically as the machine is moving (Figure 4).

For unidirectional circularity repeatability three actual paths are measured consecutively in one contouring direction, with an intermediate stop after each actual path. For didirectional circularity repeatability however six actual paths are measured consecutively, three in one contouring direction and three in the opposite contouring direction, with an intermediate stop after each actual path.

The following definitive statements may be recorded :

- ☐ Unidirectional circular repeatability
- ☐ Bidirectional circular repeatability
- ☐ Circularity

Circularity errors are influenced by both geometric deviations and deviations caused by the numerical control and the drives. Geometric deviations may include : accuracy of positioning; backlash or reversal; and angular, straightness and squareness errors between linear motions; while deviations caused by the NC and drives could include : circular interpolation, following errors, influence of acceleration and the compensation of reversal errors. These parameters may be corrected and/or compensated for so that circularity values can be optimised for each machine so machining accuracy may be consistently of a higher order.

5. CALIBRATION STANDARDS FOR MACHINE TOOLS

The introduction of BS3800 : Part 2 within the BS3800 series of standards gives the machine tool industry-both manufacturers and users alike-the means for fully testing the accuracy characteristics of their machines. Companies who require positioning accuracy testing only may use Section One of the standard, while those companies who require testing of all six degrees of freedom along linear axes can of course use both sections.

At International Standards levels the accuracy and repeatability standard ISO 230-2. 1988 is undergoing revision and later this year a working draft should be available for public comment. Further, the formation of another ISO working group concerning the measurement of

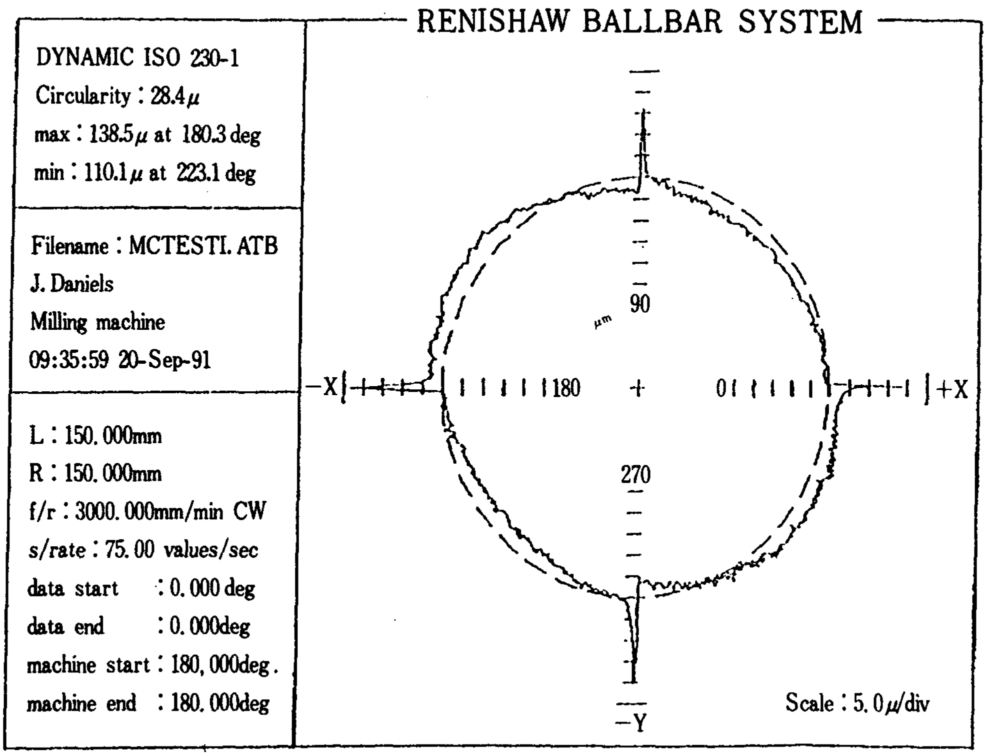

Fig. 4 Circularity Errors-Analysis to Latest ISO Document

circularity shows that other aspects of machine tool performance have been identified as of use to the machine tool manufacturer and user alike in ensuring that machines achieve their full performance.

Finally, laser calibration of the principal degrees of freedom along linear axes coupled with circularity checks to national and international standards have showed an excellent corelation of results with those from the machining of test pieces[11]. It can therefore be concluded that circularity measurement is a major step forward in the performance evaluation of machine tools which complements periodic laser calibration tests performed prior to the sometimes time consuming and tedious process of cutting tests.

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