



Machine tool accuracy and repeatability - a new approach with the revision of ISO 230-2

D.M.S. Blackshaw

ITP Ltd., Rugby, Warwickshire CV21 3RQ, UK

Abstract

Machine tool manufacturers and users will be well versed in the determination of accuracy and repeatability of their machines according to the major national and international machine performance standards. These standards are concerned with measuring the repeatability and accurate positioning of moving parts of a numerically controlled (NC) machine along or around each of the linear and rotary axes in turn.

Since the publication of the international standard some 9 years ago, coupled with the knowledge of many thousand machine tool calibration exercises world-wide and new recommendations from ISO Geneva, the working group (ISO / TC39 / SC2 / WG2) charged with revising the international standard made further wide-ranging recommendations on the subject of how to measure machine tool accuracy and repeatability. These recommendations have culminated in a final draft standard (FDIS) being published which is at present being considered within ISO member countries for publication as a revision to the existing standard.

This paper describes the changes within the standard, highlighting the differences in the practical approach to machine tool calibration, along with the changes that have now been made in the statistical calculation of the results for machine acceptance.

Background to positioning accuracy and repeatability standards

Positioning accuracy and repeatability measurement of both linear and rotary axes may be assessed to the British and International standards BS3800 : Part 2 [1] and ISO 230-2 [2]. These standards are used in the type testing of specific machines, acceptance testing of newly installed machines, comparison testing of a range of machines, periodic verification (i.e. annual recalibration), and linear error compensation to the machine tool controller to ensure continuing accuracy.

The standards describe methods involving repeat measurements at each target position along the axis of test [3]. The existing standards state that the number of measurements and nature of the errors do not allow the confidence



level of the results to be estimated accurately, but a Gaussian distribution may nevertheless be assumed and a calculation of ± 3 standard deviation repeatability bands has been shown in practice to have an adequate confidence level (99.7%). Provided the specified procedure is followed it is stated that acceptable results should be obtained.

GUIDE TO THE EXPRESSION OF UNCERTAINTY IN MEASUREMENT

Since the publication of ISO 230-2 in 1988 further recommendations have been made on the subject of assessing accuracy and repeatability. These are contained in "Guide to the expression of uncertainty in measurement" [4], published in 1993. This Guide establishes general rules for evaluating and expressing uncertainty in measurement and is applicable to a broad range of measurements including machine tool accuracy and repeatability. It was prepared by a joint working group consisting of experts nominated by: BIPM (Bureau International des Poids et Mesures), IEC (International Electrotechnical Commission), ISO (International Organisation for Standardisation) and OIML (International Organisation of Legal Metrology).

CHANGES TO ISO / FDIS 230-2

After considering the Guide, the ISO working group TC39/SC2/WG2, charged with updating and revising ISO 230-2, decided to follow the recommendations given. This highlights two major changes to the recently published final draft ISO/FDIS 230-2 [5].

The first modification relates to the assumption of the type of distribution of positional deviations. Modified definitions in the final draft standard now use no assumptions for the shape of the new distribution and refer to 'standard uncertainties' rather than 'standard deviations', thereby deleting references to the Gaussian distribution.

Secondly, the new definition of expanded uncertainty is now ± 2 , with a 'coverage factor' of 2, instead of ± 3 standard deviations as stated previously.

The following new definitions now apply:

Expanded uncertainty - quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values.

Coverage factor - numerical factor used as a multiplier of the standard uncertainty in order to obtain an expanded uncertainty.

Calculations of repeatability and accuracy for both unidirectional and bi-directional approaches are therefore now based on the mean position deviation and ± 2 standard uncertainties.



ACCURACY AND REPEATABILITY TESTS FOR LINEAR AND ROTARY AXES

There are now three major tests described for assessing positioning accuracy and repeatability namely:

- linear axes up to 2 metres
- linear axes exceeding 2 metres
- rotary axes up to 360 degrees.

Firstly, for linear axes up to 2 metres in length, a minimum of five random target positions per metre with a minimum of five random target positions overall are to be selected along the axis. Where the value of each target position can be freely chosen it shall take the following form:

$$P = (I - 1)p + r$$

where: I is the number of current target positions

p is an interval based on a uniform spacing of target points over the measurement travel

and: r takes a different value at each target position, yielding a non uniform spacing of the target positions over the measurement travel to ensure that periodic errors, such as errors caused by the pitch of the ballscrew and pitch of linear or rotating scales, are adequately sampled.

Measurements are made according to the 'standard test cycle' which is consistent with the 'linear cycle' described in the previous ISO 230-2 standard, and five bi-directional measurement runs are performed. It should be noted that the 'quasi pilgrim step cycle' which was an optional test cycle in the previous version has now been deleted from the main body of the standard but is included in Annex A for information. This is because the results using this cycle differ from those using the 'standard test cycle'.

With the 'standard test cycle' (Figure 1), the approach to the extreme target positions from opposing directions takes place with a large difference in time intervals. However, with the 'step cycle' the approach to the target positions from either direction takes place within shorter time intervals and a longer time is taken between the measurements of the first and last target positions. As a result measurements according to the 'standard test cycle' may reflect thermal influences which can be evident in the reversal value (backlash) and the repeatability, while in the case of the 'step cycle' thermal influences may be noticeable in the range of the mean bi-directional positional deviation with the reversal and repeatability values only slightly affected by the thermal behaviour of the machine.

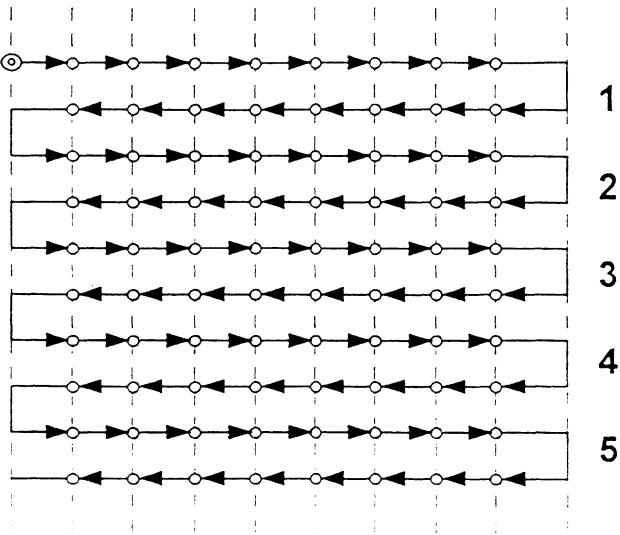


Figure 1: Standard test cycle

Secondly, for linear axes exceeding 2 metres, the whole measurement travel of the axis is tested by making one bi-directional approach in each direction at random positions but with an average interval length of 250mm. If the machine axis measuring transducer consists of several elements, for example a combination of scales, then additional target positions may have to be selected to ensure that each element has at least one target position. A further accuracy and repeatability test is also performed over a 2 metre length of axis in the normal working area in accordance with the first test outlined above i.e. five bi-directional measurement runs. It can be seen therefore that for axes longer than 2 metres there is no requirement to perform five bi-directional runs over the full axis length. This would be time consuming and leads to non-repeatable results due to thermal distortion of the machine structure and axes, as well as changes in environmental conditions over such a protracted test.

Finally rotary axis calibration is also addressed in greater detail than previously. Principal target positions of 0, 90, 180 and 270 degrees should now be included when available, along with other random target positions. the minimum number of target positions which may be measured are as follows:

Measurement travel	Minimum number of target positions
Less than 90 degrees	3
90 - 180 degrees	5
Greater than 180 degrees	8

However the inclusion of both fixed and random target positions for calibrating rotary axes precludes the traditional measuring instruments of autocollimator and optical polygon where accuracy was measured on successive faces of the polygon at equal intervals through 360 degrees. The preferred measurement system for recording both fixed increment and random positions is now a laser interferometer, complete with angular optics and a secondary high accuracy rotary table precisely centred in the middle of the rotary table under test. In this way 5 degree intervals are accurately moved and measured using the secondary rotary table while single degrees and fractions of degrees of movement are measured using the angular optics and appropriate large angle correction software.

EVALUATION AND PRESENTATION OF RESULTS

With this revision of ISO 230-2 it is important to remember that repeatability bands are calculated from standard uncertainties and the expanded uncertainty band is now ± 2 , giving a confidence level of 95%. Therefore, when comparing accuracy and repeatability figures with previous standards the new figure will always be numerically smaller as ± 2 is used instead of ± 3 .

In presenting the accuracy and repeatability results, the ISO working group decided to highlight the systematic behaviour of machine tools and added two new definitions to the draft standard which are already quoted in other national accuracy and repeatability standards. These are linear accuracy, E, corresponding to linear displacement accuracy in the American ANSI B5.54 : 1992 standard [6], and M the mean bi-directional positional deviation of an axis corresponding to Pa in the German VDI/DGQ 3441 standard [7].

The following results may be quoted for linear axes up to 2 metres and rotary axes up to 360 degrees and are shown graphically in Figure 2. The parameters marked with an asterisk (*) give a summary of results which provide a basis for machine acceptance:

- * Bi-directional accuracy, A
Unidirectional accuracy, A (+ve approach) and A (-ve approach)
- * Bi-directional systematic deviation, E
Unidirectional systematic deviation, E (+ve approach) and E (-ve approach)
- * Range of mean bi-directional positional deviation, M
- * Bi-directional repeatability, R
Unidirectional repeatability, R (+ve approach) and R (-ve approach)
- * Maximum reversal deviation, (B)max
Mean reversal deviation, (B)mean



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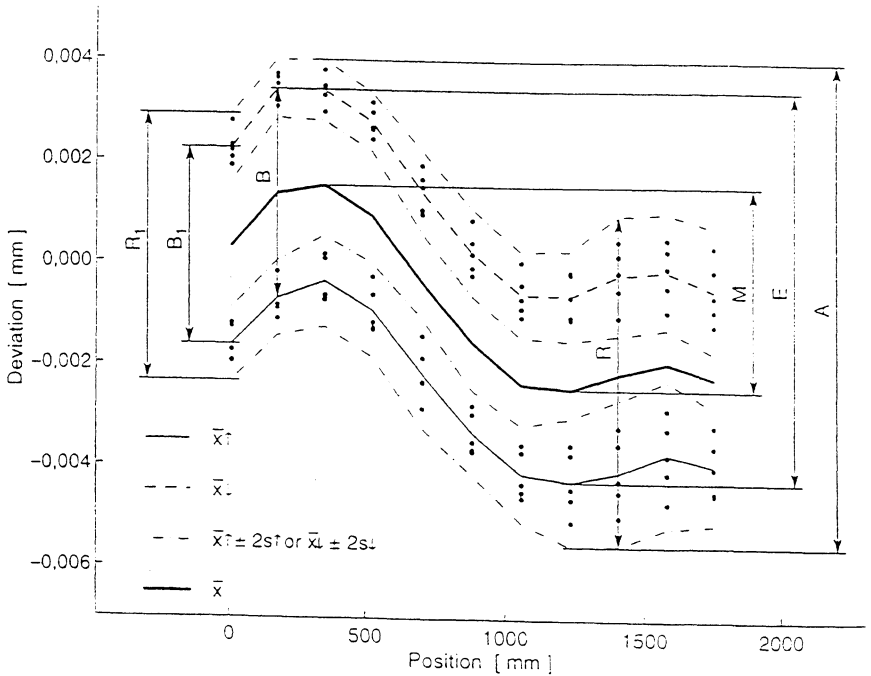
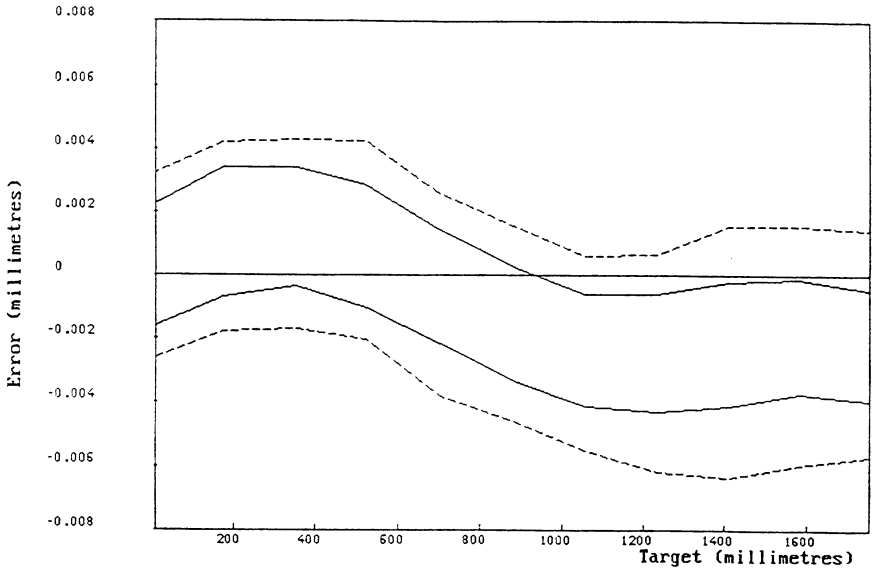


Figure 2: Graphical presentation of results

Results quoted for axes exceeding 2 metres are as follows, again parameters marked with an asterisk (*) give a summary of results providing a basis for machine acceptance:

- * Bi-directional systematic deviation, E
Unidirectional systematic deviation, E (+ve approach) and E (-ve approach)
- * Range of the mean bi-directional positioning deviation, M
- * Maximum reversal deviation, (B)max
Mean reversal deviation, (B)mean

Figure 3 gives linear positioning accuracy and repeatability results according to the existing British / ISO standard (± 3 standard deviations), while Figure 4 provides the graphical output from the revised standard (± 2 standard uncertainties).

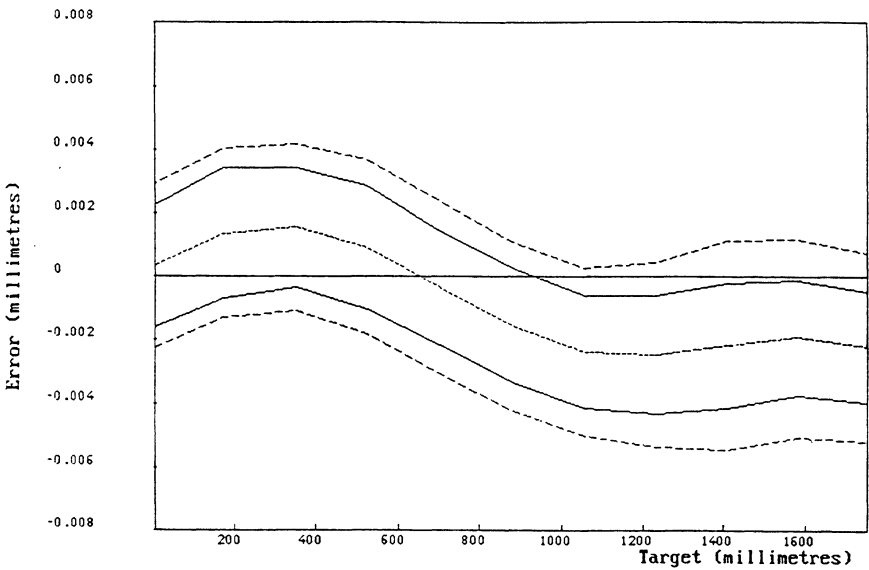


Total positioning accuracy of axis	= 0.0106mm
Mean positioning bi-directional deviation	= 0.0039mm
Bi-directional repeatability	= 0.0078mm
Unidirectional repeatability	= 0.0044mm
Mean reversal value	= 0.0037mm

Figure 3:
Accuracy and repeatability to BS3800 : Part 2 : 1991



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Bi-directional accuracy	= 0.0096mm
Bi-directional systematic deviation	= 0.0077mm
Range of mean bi-directional positional deviation	= 0.0040mm
Bi-directional repeatability	= 0.0065mm
Unidirectional repeatability	= 0.0029mm
Maximum reversal deviation	= 0.0041mm
Mean reversal deviation	= 0.0037mm

Figure 4:
Accuracy and repeatability to ISO / DIS 230-2 : 1997



A comparison of the final statements of accuracy and repeatability according to both analysis methods is now given:

	1988 - Present BS3800 : Part 2	Future ISO/FDIS
Bi-directional accuracy /mm	0.0106	0.0096
Bi-directional systematic deviation / mm	-----	0.0077
Range of mean bi-directional positional deviation / mm	0.0040	0.0040
Bi-directional repeatability / mm	0.0078	0.0065
Unidirectional repeatability / mm	0.0044	0.0029
Maximum reversal deviation / mm	-----	0.0041
Mean reversal deviation / mm	0.0037	0.0037

CONCLUSIONS

Because of changes to the accuracy and repeatability standard outlined, tests performed over the next 12-18 months should be made according to both established published standards where ± 3 standard deviation repeatability bands are calculated, and also in accordance with the draft ISO 230-2 standard where ± 2 expanded uncertainty bands are used.

It will of course be difficult for some manufacturers and users to immediately re-evaluate their own in-house accuracy specifications to conform to the new standard. But in time, and with continued use, the machine tool world will have to be comfortable with quoting both ± 3 standard deviation bands and ± 2 uncertainty bands, distinguishing between the two sets of results.

It is hoped that both machine tool manufacturers and users alike will be knowledgeable about these changes by the time the ISO / DIS 230-2 standard is published. On final publication it is very likely that the BS3800 : Part 2 standard will be re-issued in line with the contents of its sister ISO standard.



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