

General tests for machine tools

**Part 2. Statistical methods for
determination of accuracy and
repeatability of machine tools**

Committees responsible for this British Standard

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Advanced Manufacturing Technology Research Institute
 Cranfield Institute of Technology
 Department of Trade and Industry (Mechanical Engineering and
 Manufacturing Technology Division (Mmt))
 Federation of British Engineers' Tool Manufacturers
 Health and Safety Executive
 Ministry of Defence
 Society of British Aerospace Companies
 Individual experts

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Foreword

This Part of BS 3800 has been prepared under the direction of the Machine, Engineers and Hand Tools Standards Policy Committee and supersedes BS 4656 : Part 16 : 1985 which is withdrawn.

The methods described involve repeat measurements at each position but the number of measurements and the nature of the errors does not allow the confidence level of the results to be estimated accurately. Nevertheless the methods chosen, which assume Gaussian distribution, have been shown in practice to have an adequate confidence level and, provided the procedure is followed, will give acceptable results.

This standard may be used for prototype development, type testing, acceptance tests, comparison testing and periodic recalibration.

This standard is published in advance of the revision of ISO 230-2 : 1988 which is related to section 1 of this Part of BS 3800. ISO 230-2 is published by the International Organization for Standardization (ISO).

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Section 1. General

1.1 Scope

This Part of BS 3800 describes statistical methods of testing and evaluating the accuracy and repeatability of machine tools and related accessories by direct measurement on the machine.

The methods described in section 2 are for linear and rotary positioning errors and apply to numerically controlled (NC) machine tools only.

The methods described in section 3 are for angular (including pitch, roll and yaw) and straightness errors and apply to NC and manually controlled machine tools.

1.2 Test conditions

1.2.1 Environment

Where the temperature of the environment can be controlled, it shall be set to 20 °C.

NOTE. Tests may be carried out at any other ambient temperature.

The variation in temperature for 12 h before the test shall not exceed 4 °C, and during the test the variation shall not exceed 2 °C.

The machine and, if relevant, the measuring instruments, shall have been in the test

environment long enough (preferably overnight) to be in a thermally stable condition before testing. They shall be protected from draughts and external radiations such as sunlight and those from overhead heaters, etc.

In the case of linear positioning errors, if the measuring instrument incorporates compensation for environmental factors such as air temperature and pressure or for machine temperature, these shall be used to yield results corrected to 20 °C.

1.2.2 Machine to be tested

The machine shall be completely assembled and fully operational in accordance with the manufacturer's instructions. All necessary levelling operations and functional checks shall be completed satisfactorily before starting the accuracy and repeatability tests.

All tests shall be carried out with the machine in the unloaded condition, i.e. without a workpiece.

NOTE. It is normal for the measurements to be taken between the workpiece and the tool positions.

1.2.3 Warm-up

To test the machine in a normal operating condition, the tests shall be preceded by a warm-up period. The process chosen shall be recorded.

Section 2. Linear and rotary positioning accuracy and repeatability

2.1 General

This section of BS 3800 : Part 2 describes a method of measurement of linear and rotary positioning accuracy and repeatability of the moving parts along each axis of the machine of numerically controlled machine tools only.

2.2 Definitions

For the purposes of this section of BS 3800 : Part 2 the definitions given in BS 3800 : Part 1 apply together with the following.

2.2.1 target position P_j

The position to which the moving part is programmed to move. The subscript j identifies the particular position from other selected target positions along or around the axis.

NOTE. Q is the actual number of target positions used.

2.2.2 measured position P_{ij}

The measured distance which is obtained on the i th approach to the j th target position.

NOTE. n is the total number of approaches used in each direction.

2.2.3 deviation of position x_{ij}

The difference between the measured position and the target position.

2.2.4 unidirectional

Making a series of measurements in which the approaches to a target position are always made in the same direction along or around the axis.

NOTE. The symbols $\uparrow$ and $\downarrow$ signify parameters derived from a measurement made after approaches in the positive direction and the negative direction respectively, e.g. $x_{ij}\uparrow$ or $x_{ij}\downarrow$.

2.2.5 bidirectional

Making a series of measurements in which the approaches to a target position are made in both directions along or around the axis.

2.2.6 systematic error

The component of the total error that is essentially deterministic and repeatable, being wholly attributable to identifiable sources of error within the machine and measurement system.

2.2.7 random error

The component of the total error that is essentially indeterministic and unrepeatable either through uncertainty of measurement or from truly random factors associated with the machine and measurement system.

2.2.8 mean unidirectional positioning deviation $\bar{x}_{j\uparrow}$ or $\bar{x}_{j\downarrow}$ at a position P_j

The arithmetic mean of the deviations of position obtained at a position P_j in a series of n unidirectional approaches to the position.

2.2.9 mean bidirectional positioning deviation $\bar{d}_j$ at a target position P_j

The bidirectional local systematic deviation at a particular target position. This is taken as the arithmetic mean of all the individual deviations of position x_{ij} , regardless of direction.

2.2.10 reversal value B_j at a target position P_j

The value of the difference between the mean unidirectional positioning deviations at a position obtained for the two directions of travel.

NOTE. Normal lost motion or backlash is represented by a negative reversal value.

2.2.11 mean bidirectional positioning deviation $\bar{D}_p$ for the axis

The difference between the maximum and minimum values of the mean bidirectional positioning deviation $\bar{d}_j$.

2.2.12 mean reversal value $\bar{B}$ for the axis

The arithmetic mean of all the individual target position reversal values.

NOTE. Due account should be taken of any + or - signs.

2.2.13 dispersion $s_{j\uparrow}$ or $s_{j\downarrow}$

The estimator of the statistical standard deviation of the deviation values of a series of n unidirectional measurements at a position P_j . This value is found either by using the statistical standard formula or by the range method (see 2.4).

2.2.14 repeatability R_j at a target position P_j

The predicted spread of results at a given target position.

2.2.15 unidirectional repeatability R_{uj} at a target position P_j

The repeatability for one direction of travel at a given target position. The direction of travel is chosen to give the largest (i.e. worst) value.

2.2.16 bidirectional repeatability R_{bj} at a target position P_j

The repeatability for both directions of travel at a given target position.

2.2.17 repeatability R for an axis

The maximum value of the unidirectional and bidirectional repeatabilities at any position along or around the axis.

2.2.18 unidirectional repeatability R_u for an axis

The maximum value of the unidirectional repeatability R_u at any target position along or around the axis.

2.2.19 bidirectional repeatability R_b for an axis

The maximum value of the bidirectional repeatability R_b at any target position along or around the axis.

2.2.20 total positioning accuracy A_p of an axis

The maximum difference between the extreme values of deviation ($\pm 3s_j$) over all targets regardless of the direction of motion.

2.2.21 linear cycle

A test cycle in which measurements are obtained in sequence approaching each target position along the axis of test in one direction and then returning through these target positions to complete one bidirectional measurement run (see figure 1).

NOTE. A minimum of five bidirectional measurement runs should be performed.

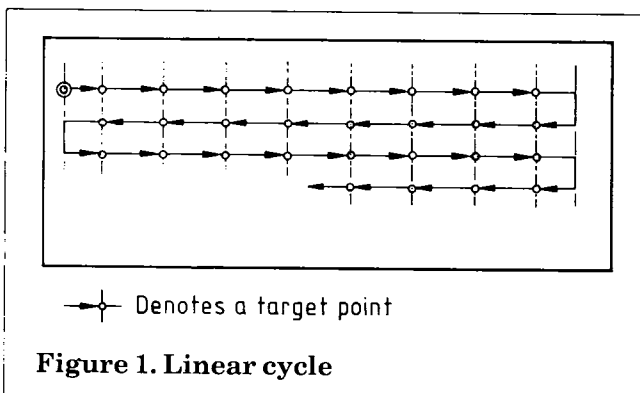


Figure 1. Linear cycle

2.2.22 quasi-pilgrim step cycle

A test cycle in which measurements are obtained in sequence such that each target position is approached a minimum of five times bidirectionally before moving to the next positions along the axis (see figure 2). There is therefore just one measurement run which starts at the near point and ends at the far end of travel.

NOTE. The quasi-pilgrim method may give slightly different results to the linear cycle method.

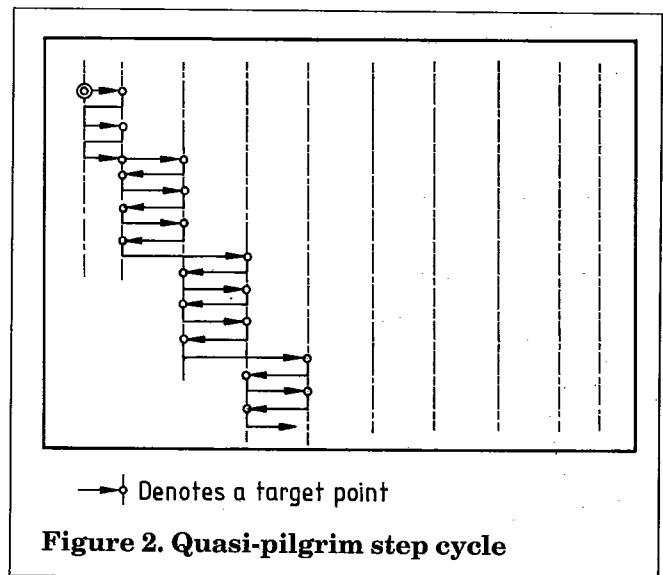


Figure 2. Quasi-pilgrim step cycle

2.3 Test procedure**2.3.1 Mode of operation**

Programme the machine to move the moving part along or around the axis under test and position it at a series of target positions so that the actual position reached may be measured and recorded. Record whichever feedrate is used.

2.3.2 Selection of target positions

Where the value of each target position can be freely chosen, select the increment X_j between target positions as follows.

$$X_j = (N \pm r_j)p$$

where

N is a suitable integer;

r_j is a random decimal fraction;

p is the largest cyclic pitch of the axis under test;

and where r_j takes a different value at each target position P_j and N is chosen to satisfy the requirements of 2.3.3.1.

NOTE 1. For $j > 1$, X_j is the distance between target position P_j and the previous target position P_{j-1} . The position of P_1 is arbitrarily placed at a distance less than Np from the start of the axis.

NOTE 2. Random target selection will have a different effect to that of fixed increment target selection on detecting cyclic error. If cyclic error is thought to be important then a separate check should be conducted.

2.3.3 Measurements

2.3.3.1 Linear positioning

On machine axes of length up to 2 m, select a minimum of five target positions per metre in accordance with 2.3.2, with an overall minimum of five target positions, uniformly spaced along the axis.

Measure all the target positions according to either the test cycle shown in figure 1 (linear cycle) or that in figure 2 (quasi-pilgrim step cycle). Approach each target position a minimum of five times in each direction.

State the test cycle chosen, figure 1 or figure 2, on the test sheet.

2.3.3.2 Linear positioning, long axes

For axes longer than 2 m, test the whole length of the axis by making at least one unidirectional approach in each direction to a target position on each element of the measuring transducer or at intervals of 250 mm where the measuring system is continuous (e.g. ball screw, rotary transducer or inductosyn tape). Record the results.

Conduct the full test described in 2.3.3.1 over a length of 2 m in the normal working region. Record the normal working region.

2.3.3.3 Rotary positioning

For rotary axes conduct tests at the principal positions 0°, 90°, 180° and 270°. If a measuring instrument with a continuous scale is available, conduct tests at a minimum of nine positions selected in accordance with 2.3.2.

If an optical polygon is used, the number of test positions shall be determined by the number of sides in the polygon. Record the type of measuring instrument used.

2.4 Evaluation of the results

For each target position P_j and for all n approaches in each direction calculate the following.

- (a) The deviation of position:

$$x_{ij} = P_{ij} - P_j$$

- (b) The mean unidirectional positioning deviation at each target position in each direction:

$$\bar{x}_j \uparrow = \frac{1}{n} \sum_{i=1}^n x_{ij} \uparrow$$

and

$$\bar{x}_j \downarrow = \frac{1}{n} \sum_{i=1}^n x_{ij} \downarrow$$

- (c) The mean bidirectional positioning deviation at each target position:

$$d_j = \frac{1}{2} (\bar{x}_j \uparrow + \bar{x}_j \downarrow)$$

- (d) The mean positioning bidirectional deviation for the axis:

$$D_p = d_{j\max} - d_{j\min}$$

- (e) The reversal value at each target position:

$$B_j = \bar{x}_j \uparrow - \bar{x}_j \downarrow$$

- (f) The mean reversal value for the axis:

$$\bar{B} = \frac{1}{Q} \sum_{j=1}^Q B_j$$

- (g) The standard dispersion at each target position in each direction:

$$s_j \uparrow = \sqrt{\left\{ \frac{1}{n-1} \sum_{i=1}^n (x_{ij} \uparrow - \bar{x}_j \uparrow)^2 \right\}}$$

and

$$s_j \downarrow = \sqrt{\left\{ \frac{1}{n-1} \sum_{i=1}^n (x_{ij} \downarrow - \bar{x}_j \downarrow)^2 \right\}}$$

Alternatively, s_j may be calculated using the range method as follows:

$$s_j \uparrow = W_j \uparrow / k$$

$$s_j \downarrow = W_j \downarrow / k$$

where W_j is the range of deviations given by:

$$W_j \uparrow = |x_{ij} \uparrow \max - x_{ij} \uparrow \min|$$

$$W_j \downarrow = |x_{ij} \downarrow \max - x_{ij} \downarrow \min|$$

and k depends on the number n of approaches to the target position and is given by the following:

n	k
2	1.128
3	1.693
4	2.059
5	2.326
6	2.534
7	2.704
8	2.847
9	2.970
10	3.078

- (i) The accuracy limits at each target position:

Higher limit H_j = maximum of $(\bar{x}_j \uparrow + 3s_j \uparrow)$
and $(\bar{x}_j \downarrow + 3s_j \downarrow)$

Lower limit L_j = minimum of $(\bar{x}_j \uparrow - 3s_j \uparrow)$
and $(\bar{x}_j \downarrow - 3s_j \downarrow)$

- (j) The repeatability at each target position:

$$R_{w\uparrow} = 6s_{j\uparrow}$$

$$R_{w\downarrow} = 6s_{j\downarrow}$$

$$R_w = \text{maximum of } R_{w\uparrow} \text{ and } R_{w\downarrow}$$

$$R_{bj} = \text{maximum of } (3s_{j\uparrow} + 3s_{j\downarrow} + |B_j|), \\ 6s_{j\uparrow} \text{ and } 6s_{j\downarrow}$$

- (k) The repeatability for the axis:

$$R_u = R_{w\text{max}}$$

$$R_b = R_{bj\text{max}}$$

- (l) The total positioning accuracy of the axis:

$$A_p = H_{j\text{max}} - L_{j\text{min}}$$

2.5 Presentation of the results

2.5.1 Record the mean positioning bidirectional deviation D_p of the axis (see 2.2.11). This is a systematic error interpreted as either:

- (a) linear positioning deviation; or
- (b) rotary positioning deviation.

2.5.2 Record the mean reversal value $\bar{B}$ for the axis. This is a systematic error interpreted as either:

- (a) linear positioning reversal error (lost motion); or
- (b) rotary positioning reversal error.

2.5.3 Record both the maximum unidirectional (stating direction) and the bidirectional components R_u and R_b of the random error of the axis. These are interpreted as:

- (a) unidirectional positioning repeatability; and
- (b) bidirectional positioning repeatability.

2.5.4 Record the total positioning accuracy A_p of the axis.

2.5.5 Record the results graphically to show the $\pm 3s_j$ values and the mean values for each direction. In addition, where appropriate, all runs in each direction shall be displayed.

NOTE 1. A typical set of results is shown in table 1. Typical graphical presentations of the results given in table 1 are shown in figure 3.

NOTE 2. Positioning accuracy is normally stated over the entire length of the axis; however, if required, the principle parameters may be specified over a working length of 300 mm as well.