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3D MACHINE TOOL ACCURACY MEASUREMENTS

Keywords

Vector Bar, machine tool accuracy, accuracy measurements.

Abstract

In this paper the purposes of machine tool accuracy measurements are described. The main kinds of accuracy tests and methods are characterised, and a new method for 3D accuracy measurement is shown. Advantages and disadvantages, possibilities and limitations of different methods (used in industry and developed in laboratories) are presented.

Introduction

There are a few ways to improve the quality of parts machined on the machine tool, which increase their dimensional and geometrical accuracy and surface quality. One of them is testing the machine tool accuracy and decreasing an influence of this important factor. The best results are given by the post-process method, because the machined parts are measured after machining, so it is possible to take into consideration the different factors connected with the cutting process (e.g. cutting forces, tool condition) [1]. When the difference between the machined part and their virtual (mathematical or CAD) model is known, it is possible to change the cutting process (cutting conditions, parameters, cooling…) or machine settings. Measurements can be done in a separate place (e.g. on Coordinate Measurement Machine) or directly on the machine tool. The post-process method is dedicated for large-lot production and mass production, because it is time- and cost consuming. In many cases there are problems with measuring the accuracy of the measuring equipment or with the effective methods for data analysis. Checking parts according to the American standard is not universal, because the sources of errors are not recognised, and it is not possible to check 100% of the machined parts and some of them may not be corrected. So a faster and cheaper way is improving machine tool accuracy before machining [2].

Machine tool accuracy can be tested during operation or in down time. Many different devices are used to measure motion accuracy – primary factor that influences machining accuracy [3] – and diagnose NC machine tool errors, because this kind of method gives more information about errors and their potential sources [4]. Presently, the NC machine tools are the basic manufacturing equipment. The introduction of coefficient correction to the NC machine tool compensation table simplify and speed up all procedures for improving machine tool accuracy.

1. Existing methods for 3D measurement

A large number of dynamic motion accuracy measuring methods for NC machine tools have been proposed, including the commonly-used double ball bar (DBB) method and Cross Grid (KGM). Some of these methods have also been established by an ISO standard. They give the possibility to define different types of errors: e.g. stick-slip, reversal pikes, scale errors, straightness, squareness, backlash and lateral play [5]. Also errors of the tables' control system or feed speed can be determined. A large majority of measurement equipment allow testing accuracy in 2D (measuring points are spaced on a plane), with fixed measuring path (e.g. circular path in DBB method) or free form path. CAM systems allow generating NC programs with different strategies, not only with a constant step between following machining layers; therefore, testing NC programs (e.g. for milling machine tools) require measurements in 3D.

The three-dimensional material probes (in a different shapes and configurations – Fig. 1) allow us to test the positioning accuracy in 3D. A tool probe is fixed on the tool holder instead of the machine tool, and it gives a signal at the moment of contact with the characteristic elements of the probe (e.g. holes, balls, planar planes).

An interesting solution for a five-axis machine was proposed by Swiss Federal Institute of Technology (ETH) in Zurich [7]. This device, called R-test, can be used for testing circular interpolation and the movement synchronisation of tool holder and rotary table. The three analogous incremental probes with a measuring range 12 mm are placed orthogonal to each other and with an angle of 45^{o} to the table (Fig. 2).

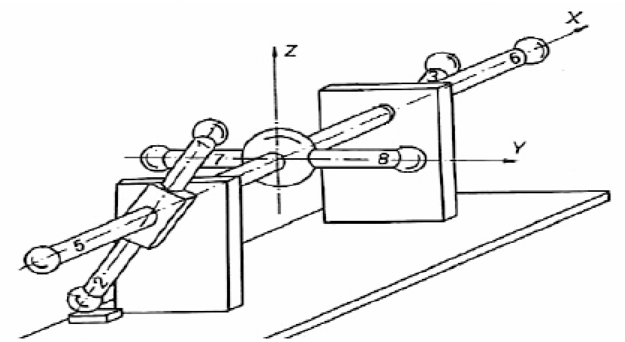


Fig. 1. The rotary material probe [6]

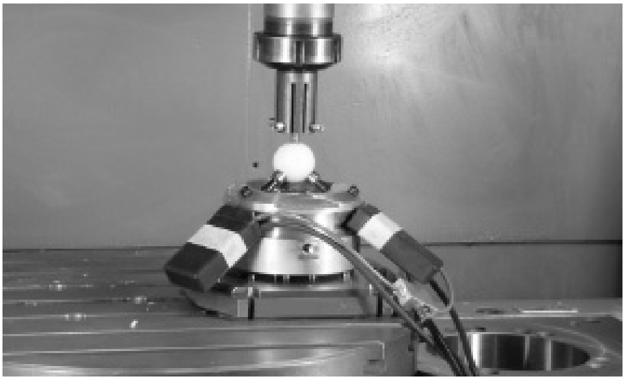


Fig. 2. R-test mounted on five axis machine tool [7]

A ceramic sphere is brought in contact with all probes at the same time. The three values of measurement (from each probe) directly describe the 3D displacement of the sphere. The main limitation of this method is the short measuring range (about ± 3mm in each direction), so it can not be used for free-form tests in 3D.

The Laser Ball Bar (LBB) with three measuring arms has a wider measuring range (approximately 385mm) [8]. It is the final version of LBB, because its prototype had only one arm and socket. The optical measurement inside the bar ensures higher accuracy and resolution, a rigid telescoping connection between the two balls (on the opposite site of bar) extended the measuring range. It was necessary to change the socket position in other places in a machine tool workspace to check the points' position in 3D (the measure of changing bar's length does not give enough data). The differences between theoretical and real socket's position give additional errors. A better solution is using three arms at the same time (Fig. 3). All bars are connected with a magnetic socket at the bottom and have a common ball-and-socket on the top.

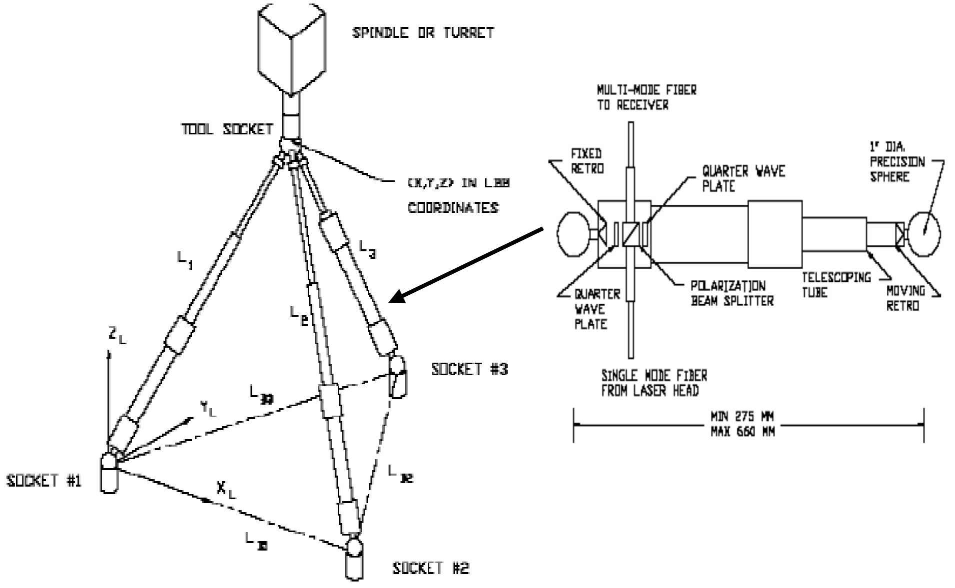


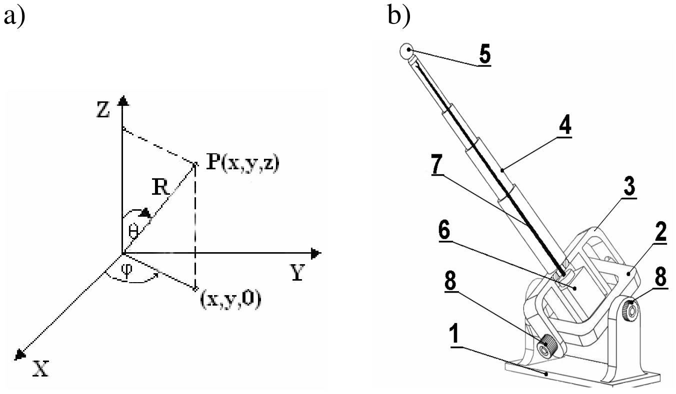
Fig. 3. The tree-arms Laser Ball Bar [8]

High cost of the device and complicated measurement algorithms are the disadvantages of this solution.

2. Designed devices for accuracy measurements

The short drawback of existing methods and equipment (commercial solutions, prototypes and methods described in patents) demonstrate the needs of researches in the machine accuracy measurement field, so at Warsaw University of Technology a few methods of measurement were proposed.

It is necessary to measure two angles and one linear displacement to determine a point's position in a sphere (Fig. 4a). The simplest way is using laser angle encoders (e.g. Canon or Sony encoders) and a laser interferometer (Fig. 4b). The total accuracy and the resolution of measurement will be high, but the cost will also be high. Some applications (e.g. some kinds of industrial robots) do not need a very high accuracy, so laser interferometer can be replaced by a wire sensor.



1 – base,
2 – Cardan joint,
3 – knuckle,
4 – telescope tube,
5 – ball-and-socket,
7 – wire sensor or interferometer,
8 – angle encoder

Fig. 4. Configuration of spherical coordinate system (a) and an example of device for define point's position in 3D (b)

One of the proposed methods suggested using a CCD matrix and a laser diode to measure the angle in a space (instead of two angles on perpendicular planes). In this case the mechanical construction will be simpler (Fig. 5).

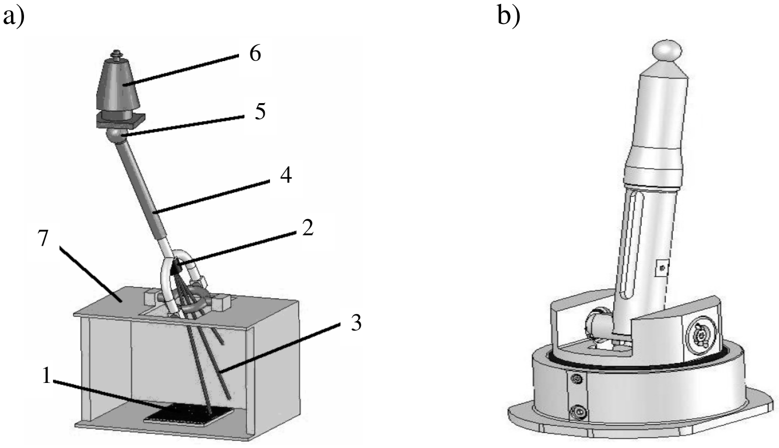


Fig. 5. The concept of the Laser Vector Bar (a) and its practical application (b) 1 - CCD matrix, 2 – laser diode, 3 – laser beam, 4 – telescope tube with optical measurement of linear displacement, 5 – ball-and-socket, 6 – tapered holder

The main problem with this application is temperature stabilisation and the deformation of the laser beam on the matrix. The beam in the cross-section is not circular but elliptical and changes its size and shapes in a different angular position of the telescope tube. Furthermore, the matrix face changes its temperature – according to the break time of the holder during the angular movement. It is necessary to use optical filters for separating other light waves, because the white light is random noise, which changes the digital readout (the average of point's position from several pixels and interpolation on the pixel premises). The small dimensions of the CCD matrix and an important factor of the Cardan's joint rotation centre position (the increasing of distance between matrix and the laser diode increase measuring resolution, but decrease measuring range) force the introduction of the optical diffraction effect; therefore, the whole device will be much more complicated.

These disadvantages were eliminated in the mechanical solution (Fig. 6), which resolve problems with the laser beam and the CCD matrix.

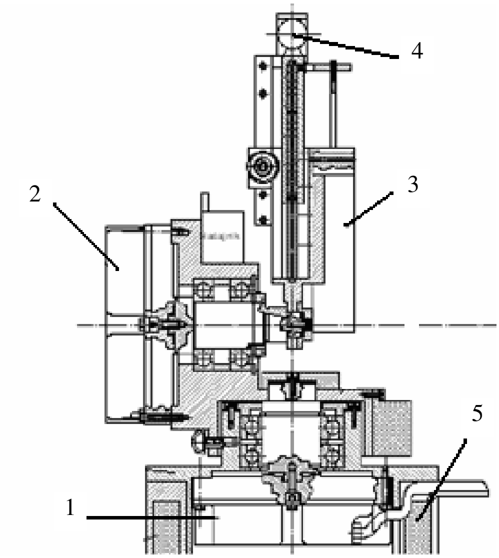


Fig. 6. The mechanical solution of Vector Bar: 1, 2 – optical angle encoder, 3 – linear encoder, 4 – ball-and-socket, 5 – magnetic socket (connection between the device's housing and the machine table)

Fig. 6 shows a device called a Vector Bar, with two angle encoders (one of them was mounted to the fixed part of the housing and the other one to the movable part) and one linear encoder. Encoders measure shafts rotation angles, which have precision ball bearings. The linear encoder was mounted to the arm with a linear guide along the vertical axis. Precision mechanical angle encoders have had large diameters and mass (approximately 3.5 kg), so the problem was with maintaining the construction's rigidity and perpendicularity of the axes. The short measuring range of the linear encoder limited the possibilities of practical use.

3. The final solution

The final solution also has two angel encoders, but in the form of rings with small laser read heads. The rings are fixed to the vertical and horizontal shafts, and they rotate together with them. The linear encoder goes through the vertical axis - to the opposite site in comparison to the ball-and-socket (Fig. 7). Special requirements for manufacturing devices impose some limitations. Devices should be noise and mechanical resistant. The presented solution does not have glass scale, mirrors or long distance light beams. Axial clearance between the read head and the encoder's ring is 0.8 mm and encoder's scale is protected against mechanical damage. The ball linear encoder is oil and water resistant, and it is not sensitive to vibration.

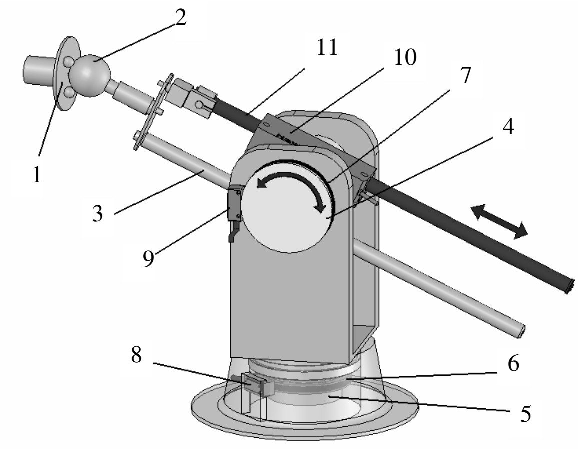
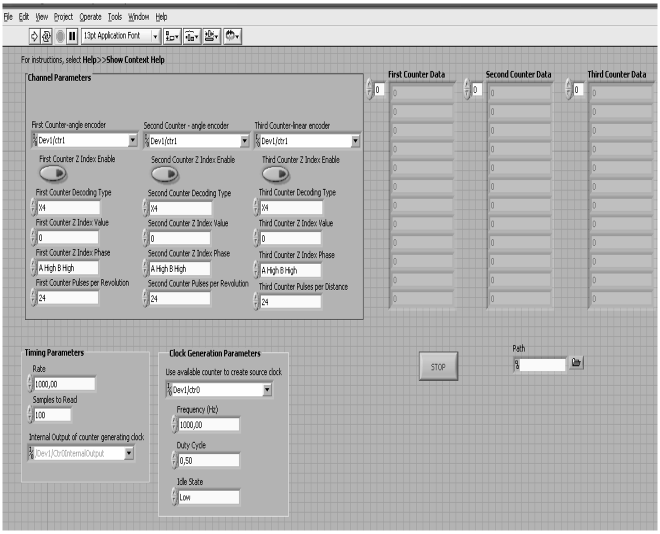


Fig. 7. Vector Bar with ring rotary encoders and a ball linear encoder: 1 – magnetic socket, 2 – ball-and-socket, 3 – ball linear guide, 4 – horizontal shaft, 5 – vertical shaft, 6 and 7 – ring of angle encoder, 8 and 9 – read head of angle encoder, 10 – read head of linear encoder, 11 – shaft of linear encoder

The angles and radius measurement errors are independent, so the calculation of errors can be considered separately, but the point's position in the spherical coordinate system depends on each of them. All of the data collected from encoders must be synchronised - it is task for a DAQ card and software (Fig. 8). The high resolutions of measurements impose conditions of sampling frequency and force the buffering of data. Then the measurement data can be saved in a file and analysed. Numerical data gives less information about machine tool accuracy directly than does their graphical representations.



For instructions, select **Help>>Show Context Help**

Channel Parameters

First Counter-angle encoder: Dev1/ctr1
First Counter Z Index Enable
First Counter Decoding Type: X4
First Counter Z Index Value: 0
First Counter Z Index Phase: A High B High
First Counter Pulses per Revolution: 24

Second Counter - angle encoder: Dev1/ctr1
Second Counter Z Index Enable
Second Counter Decoding Type: X4
Second Counter Z Index Value: 0
Second Counter Z Index Phase: A High B High
Second Counter Pulses per Revolution: 24

Third Counter-linear encoder: Dev1/ctr1
Third Counter Z Index Enable
Third Counter Decoding Type: X4
Third Counter Z Index Value: 0
Third Counter Z Index Phase: A High B High
Third Counter Pulses per Distance: 24

First Counter Data: 0
Second Counter Data: 0
Third Counter Data: 0

Timing Parameters

Rate: 1000,00
Samples to Read: 100
Internal Output of counter generating clock: /Dev1/Ctr0InternalOutput

Clock Generation Parameters

Use available counter to create source clock: Dev1/ctr0
Frequency (Hz): 1000,00
Duty Cycle: 0,50
Idle State: Low

Path

Fig. 8. An example of LabView program for reading data from two angle encoders and one linear encoder

The knowledge about encoders' accuracy allows us to calculate the theoretical influence of them on the total measurement device uncertainty. These calculations do not regard the influence of temperature, backlashes and runout of bearings but show the main principle of error distribution on workspace. In the Fig. 9, the changes of influence of the linear encoder in 2D measurement (with fixed vertical shaft) are shown. Only a small part of the measuring space was taken into consideration. The influence of radius measurement accuracy was between 30% and 100%. The maximum was in the horizontal bar position (Fig. 9).

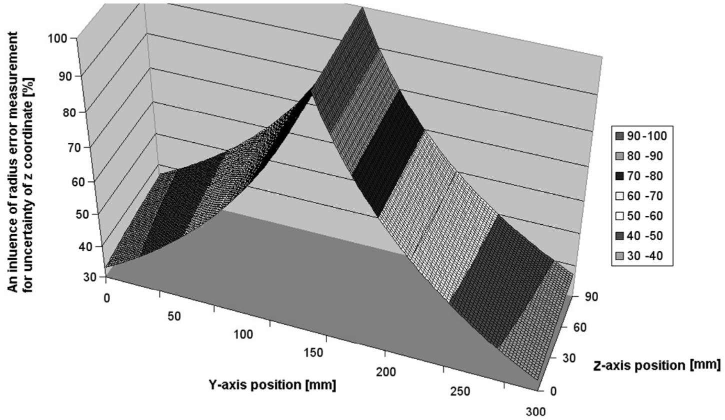


Fig. 9. An influence of radius error measurement for the uncertainty of z coordinate

Acknowledgements

Scientific work financed by the Ministry of Science and Higher Education and carried out within the Multi-Year Programme "Development of innovativeness systems of manufacturing and maintenance 2004–2008".

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Reviewer:
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Badanie dokładności maszyn NC w 3D

Słowa kluczowe

Badanie dokładności, pomiary 3D, Vector Bar, maszyny NC.

Streszczenie

W artykule opisano rolę i potrzebę badania dokładności maszyn NC. Dokonano przeglądu istniejących metod i urządzeń do sprawdzania dokładności maszyn o przynajmniej trzech osiach sterowanych numerycznie (3 osie liniowe). Przedstawiono opracowane w ramach badań projekty urządzeń pomiarowych oraz oryginalne rozwiązanie, nazwane Vector Bar. Omówiono budowę zaprojektowanego urządzenia oraz jego podstawowe cechy.