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ORIGINAL ARTICLE

Comparative study of error determination of machine tools

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Abstract

The increasing demands of highly precise industrial products lead to continuous seeking for the improvements in cabapility of manufacturing machines, i.e., machine tools. Machine tools include different types of manufacturing machines, i.e., turning, lathe, drilling, and milling machines whatever computerized numerical control (CNC) type or manual type. The cabaplity improvement in machine tools requires a real understanding of their productivity, accuracy, and operating parameters, i.e., their geometrical errors. These errors can be accurately identified through measurements with highly accurate measuring instruments. These machine errors have different error sources. The angular errors, horizontal and vertical straightness errors, paralleism errors, and squarness errors are clear examples for these sources. In this work, a comparative study for the determination of machine tools errors is carried out. Two main instruments of laser interferometer system and autocollimator system are used. The geometric errors are identified, measured, and analyzed.

Keywords Machine Tool · Laser interferometer · Autocollimator · Dimensional metrology

1 Introduction

The field of machine tool metrology has a strong contribution in industrial production. The family of machine tools includes different types of production machines, i.e., turning, lathe, drilling and milling machines with computerized numerical control (CNC) type or manual type. Understanding of geometrical errors of these machines is very important to improve their performance and capabilities which reflects on the accuracy of their products. Errors of machine tools error can be identified as the differences between the actual tool position and the programmed one [1]. These differences can be due to the errors in the machine tool itself, control, and measuring system errors and errors arising from the process of manufacturing or the environment. The machine tool errors can be divided into two main types; systematic and random errors. Systematic errors can be compensated with an accuracy depending mainly on their identification precision. Random errors may be due to the fluctuation in environmental temperature. Random errors need to be adapted and controlled [2]. In general, the sources of errors can be mainly due to one of three kinds of errors: (I) thermal errors due to temperature variation of the machine tool's subassemblies caused by their work. (II) Thermal stability on the floor shop and the accumulation of heat in the machine tool's closed spaces affect its precision. A change in ambient temperature by a few degrees celsius may result in spindle displacement by as many as tens of micrometers. (III) Geometrical errors that describe the machine tool precision. For I and II error kinds, their effects can be reduced to minimum effect through controlling of the environmental temperature and temperature rising during the production process. For III error kind, the errors should be well identified, measured, and compensated through the CNC control system [3]. The geometrical errors of machine tools are not straightforward to be simply determined. Types of geometrical error components depend on the machine tool design, mainly on the number of controlled linear and rotational axes, Fig. 1. The number of geometrical errors differs from machine tool type to another [4, 5]. For three-axes machine type, there are 21 component errors, 9 of angular errors (pitch, yaw and roll) in X, Y, and Z axes, 3 linear positioning errors, 3 horizontal straightness, 3 vertical straightness, and 3 squareness errors in the three axes.

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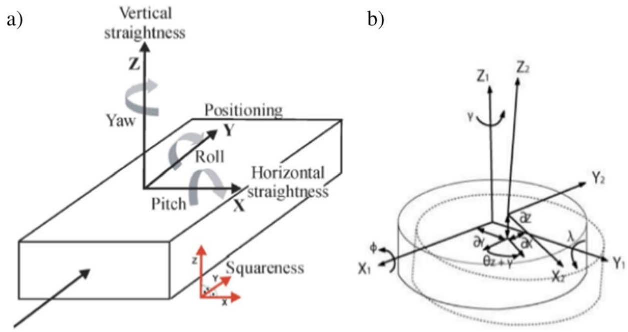
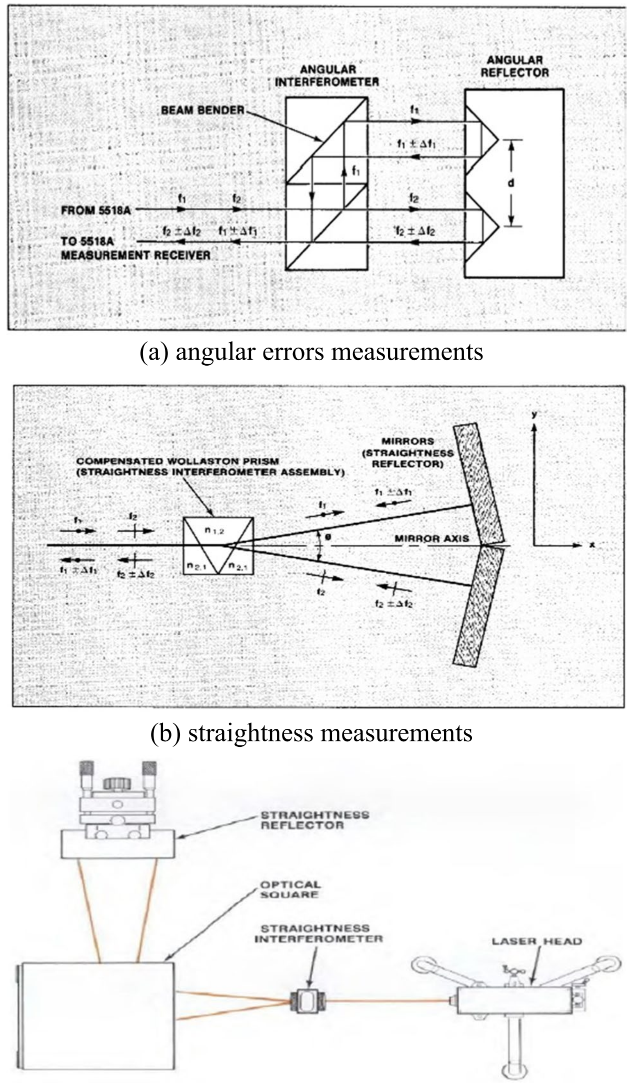


Fig. 1 Geometrical errors in 3 axes: (**a**) linear axis, (**b**) rotary axis [1]

Fig. 2 CNC machine of vertical turning centering type



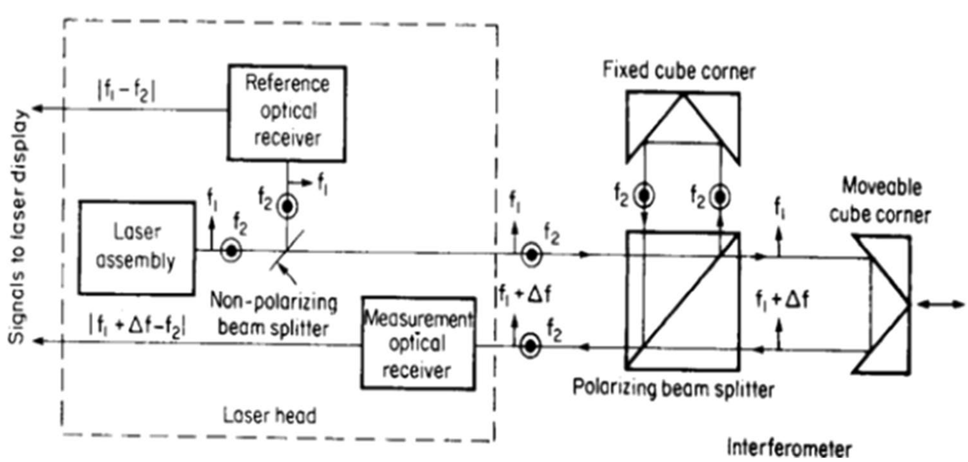
(a) angular errors measurements

(b) straightness measurements

(c) squareness measurements

Fig. 4 Measurement setup by laser interferometer system

Fig. 3 Linear measurements principle by laser interferometer system



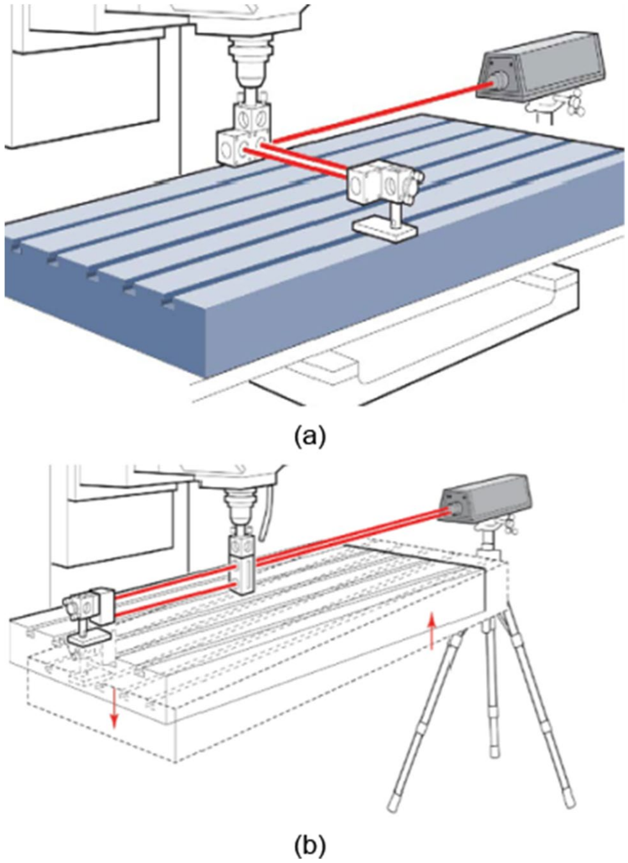


Fig. 5 Angular errors measurements, **a** yaw and **b** pitch

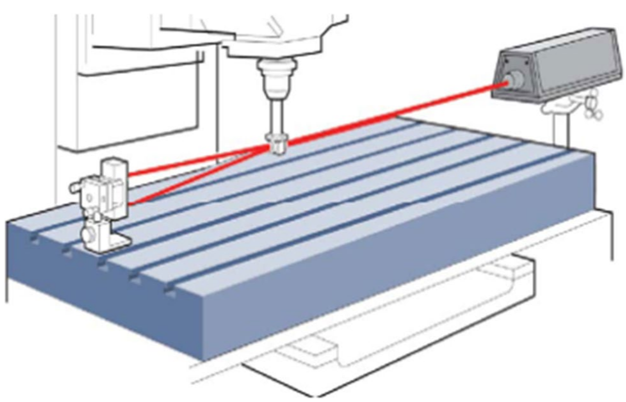


Fig. 6 Straightness measurements

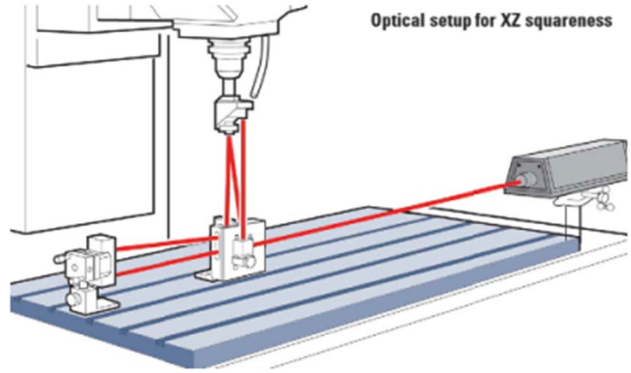


Fig. 7 Squareness measurements. **a** Rectangular shape, **b** circular shape

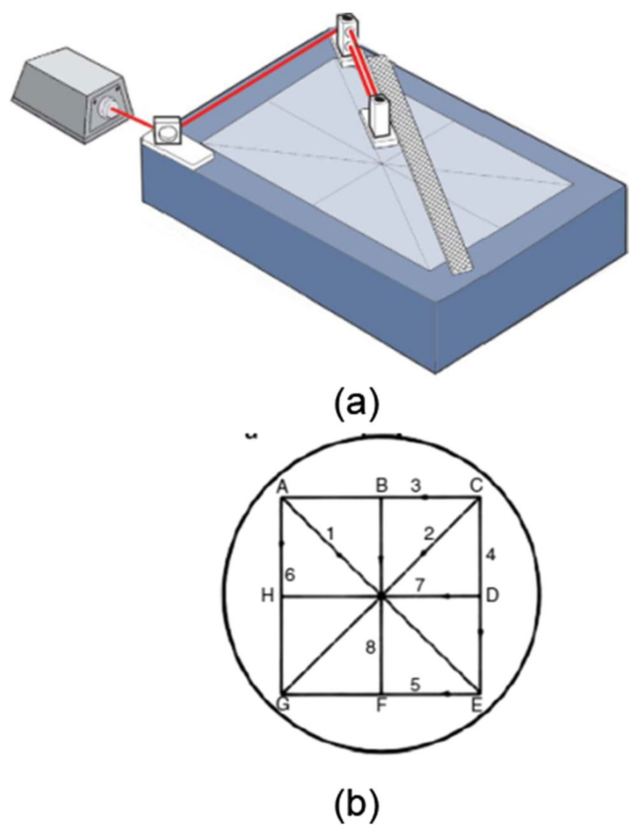


Fig. 8 Flatness measurements, **a** rectangular shape, **b** circular shape

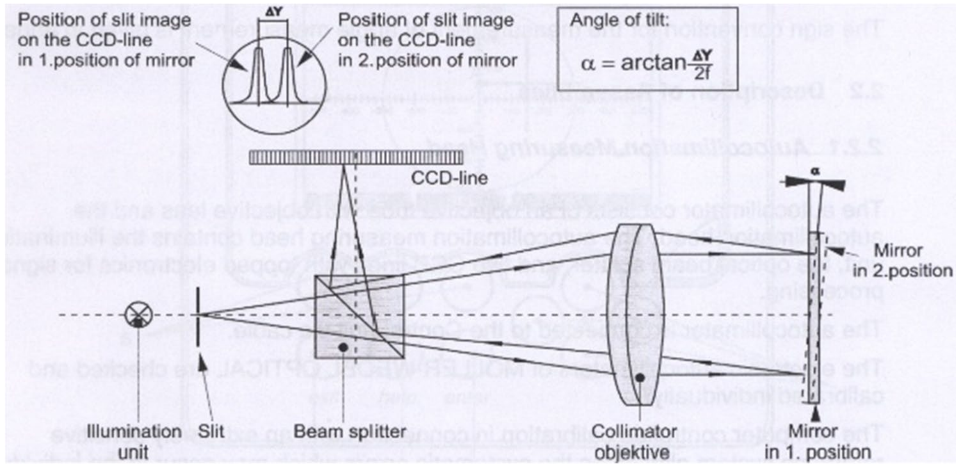


Fig. 9 Measurement principle by autocollimator system

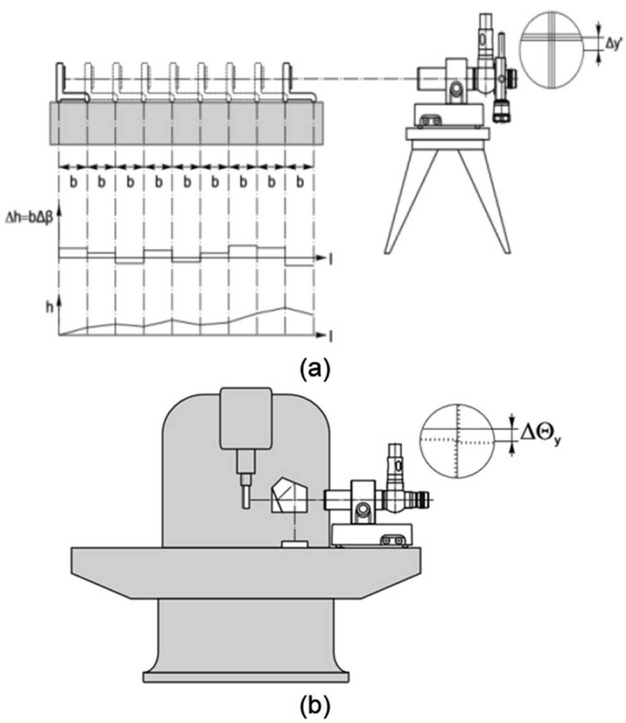


Fig. 10 Straightness and squareness measurements by autocollimator system

The measuring instruments and methods that used to identify these geometrical errors can be indirect and direct methods [2, 6, 7]. Indirect methods may be double ball bars (DBB) and optical cross grids. The accurate standards are used as quick identification the machine tool's accuracy and its errors. The ball bar specifications can be as follows: accuracy of ± 1.25 mm, resolution of 0.1 mm, and maximum sampling rate of 1000 per second. The cross-grid method serves mainly the purpose of evaluating static and dynamic machine tool errors.

Direct methods [5–9] include optical and electronic measuring instruments, i.e., autocollimators, 1D laser interferometer system, laser ball bars, 3D LBB instrument, and tracking lasers with/without active target, which are examples of such methods [10–13]. The autocollimators and 1D laser interferometer system comes in the first as the most versatile and more precise instruments among all instruments that used in geometrical error determination and accuracy identification of machine tools [14, 15].

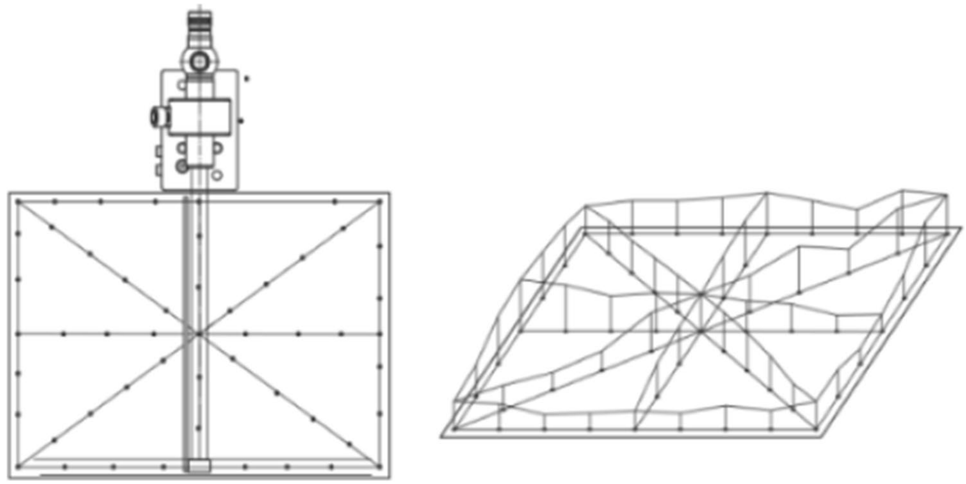


Fig. 11 Flatness measurements by autocollimator system

Table 1 Pitch errors measurements

Axis	Instrumentation	Pitch errors, arcs
X axis	Laser interferometer	29.56
	Autocollimator	26.6
Z axis	Laser interferometer	4.21
	Autocollimator	0.8

Fig. 12 Straightness measurements by hand tools

Table 2 Yaw errors measurements

Axis	Instrumentation	Yaw errors, arcs
X axis	Laser interferometer	32.56
	Autocollimator	10.4
Z axis	Laser interferometer	2.26
	Autocollimator	1.2

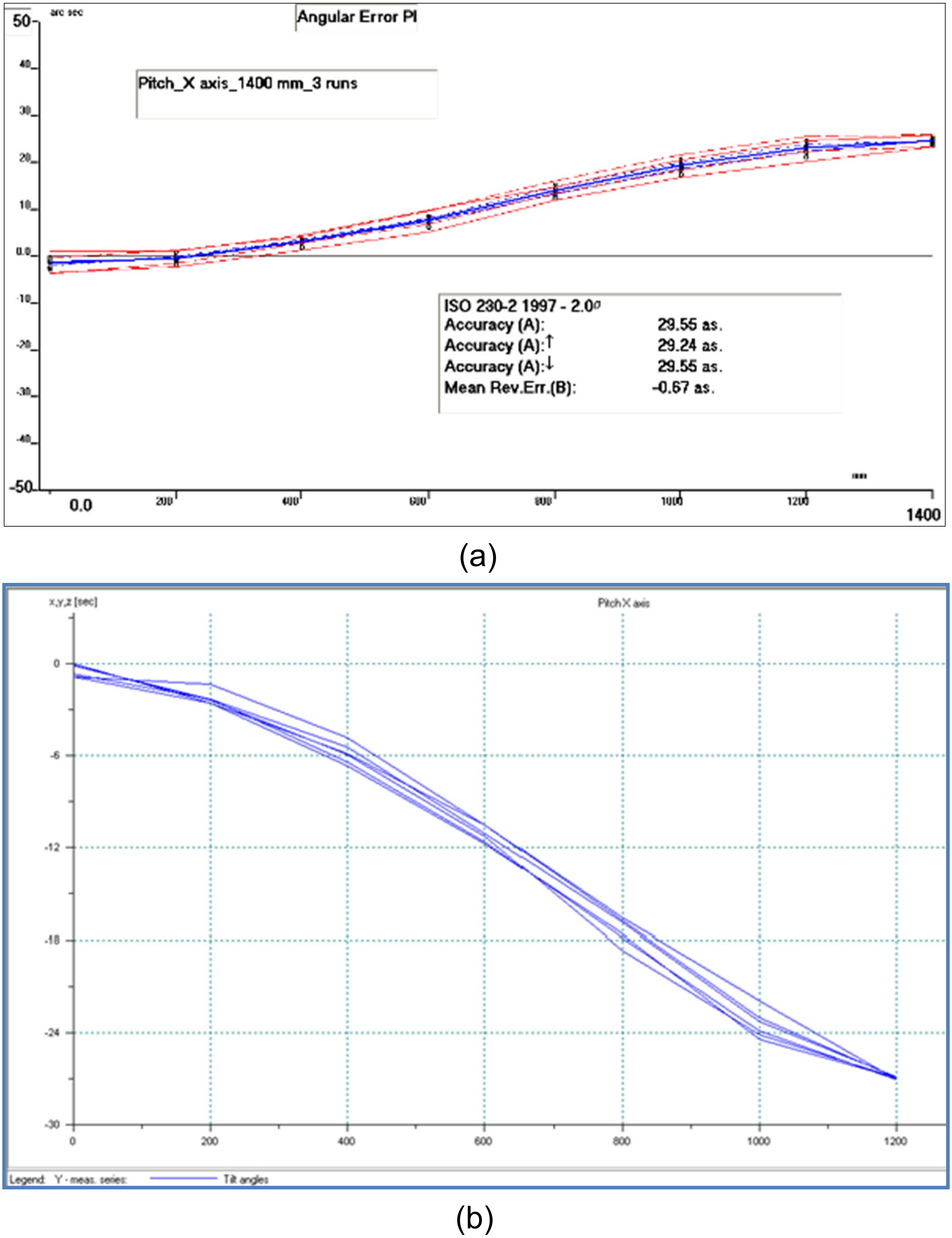


Fig. 13 Pitch measurements in *X* axis **a** laser interferometer, **b** autocollimator

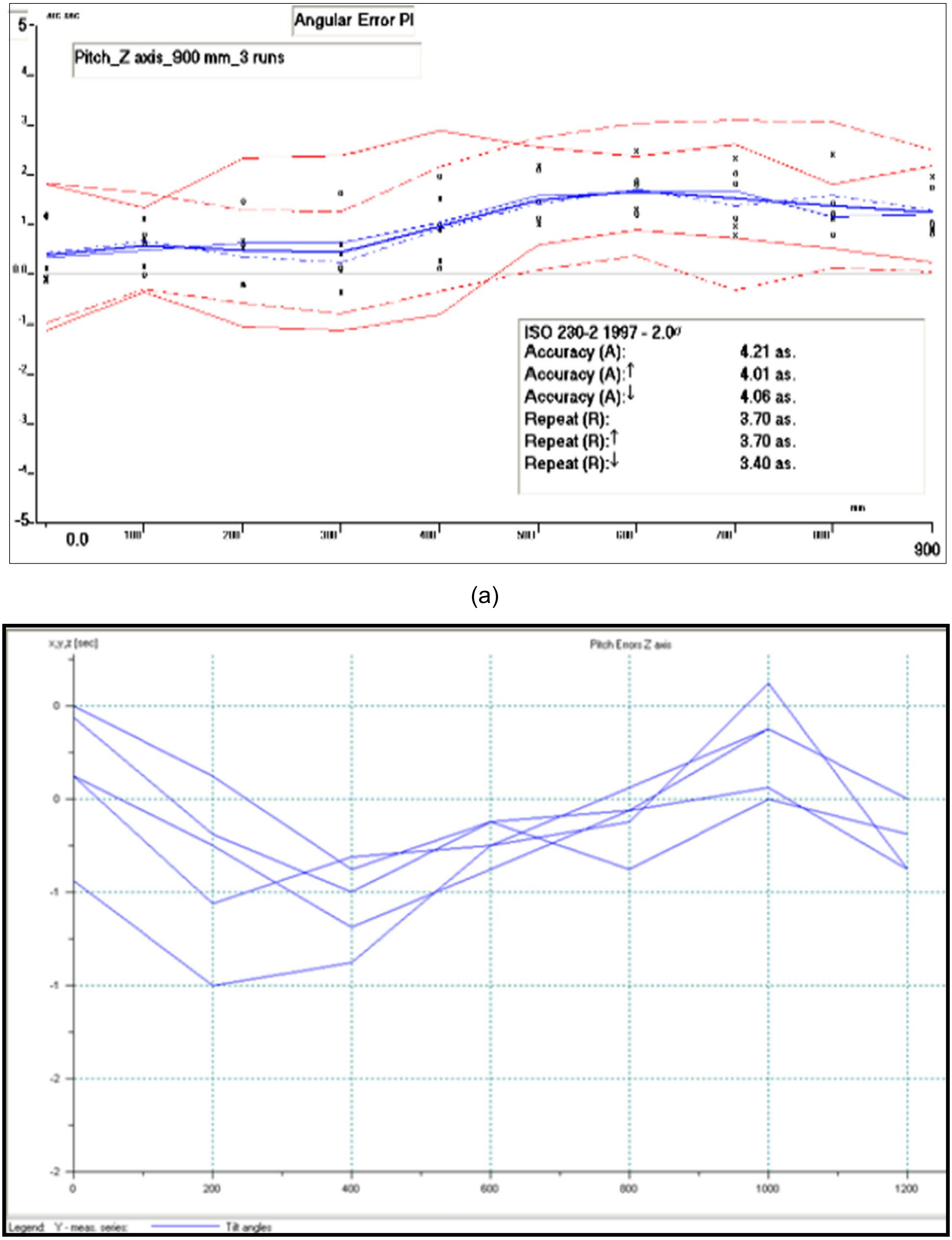
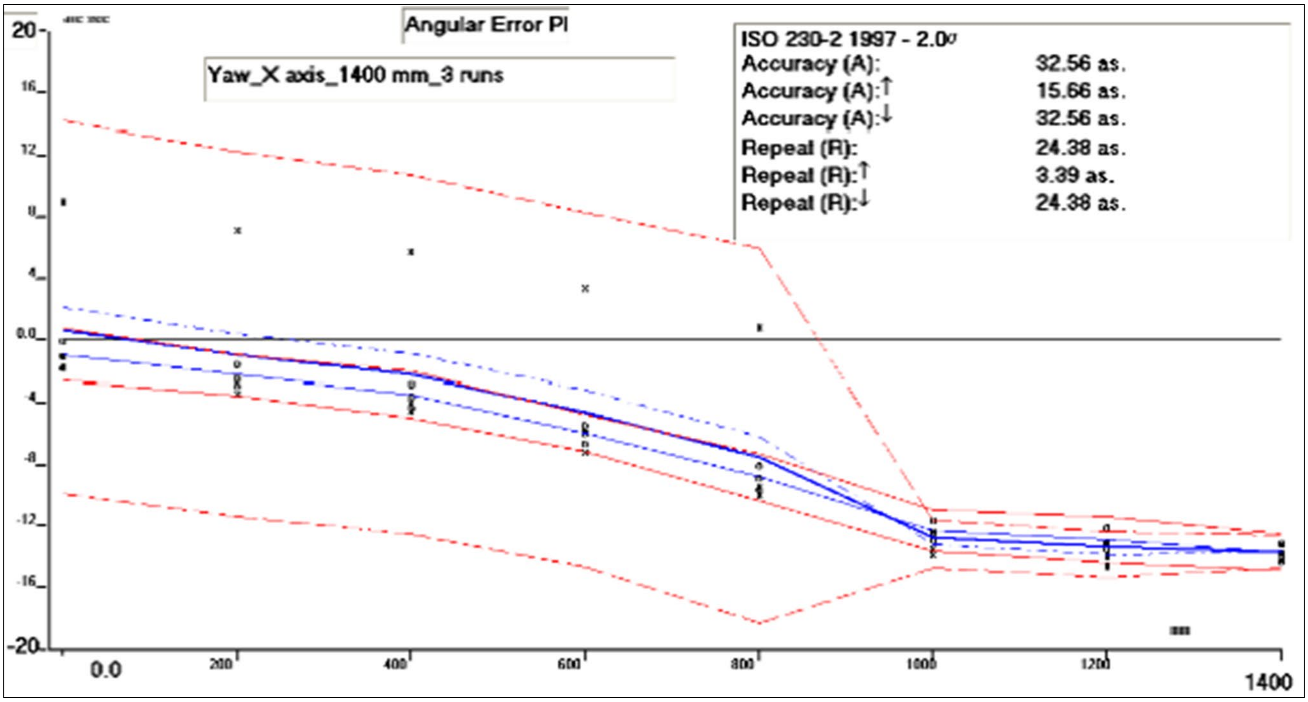


Fig. 14 Pitch measurements in Z axis **a** laser interferometer, **b** autocollimator



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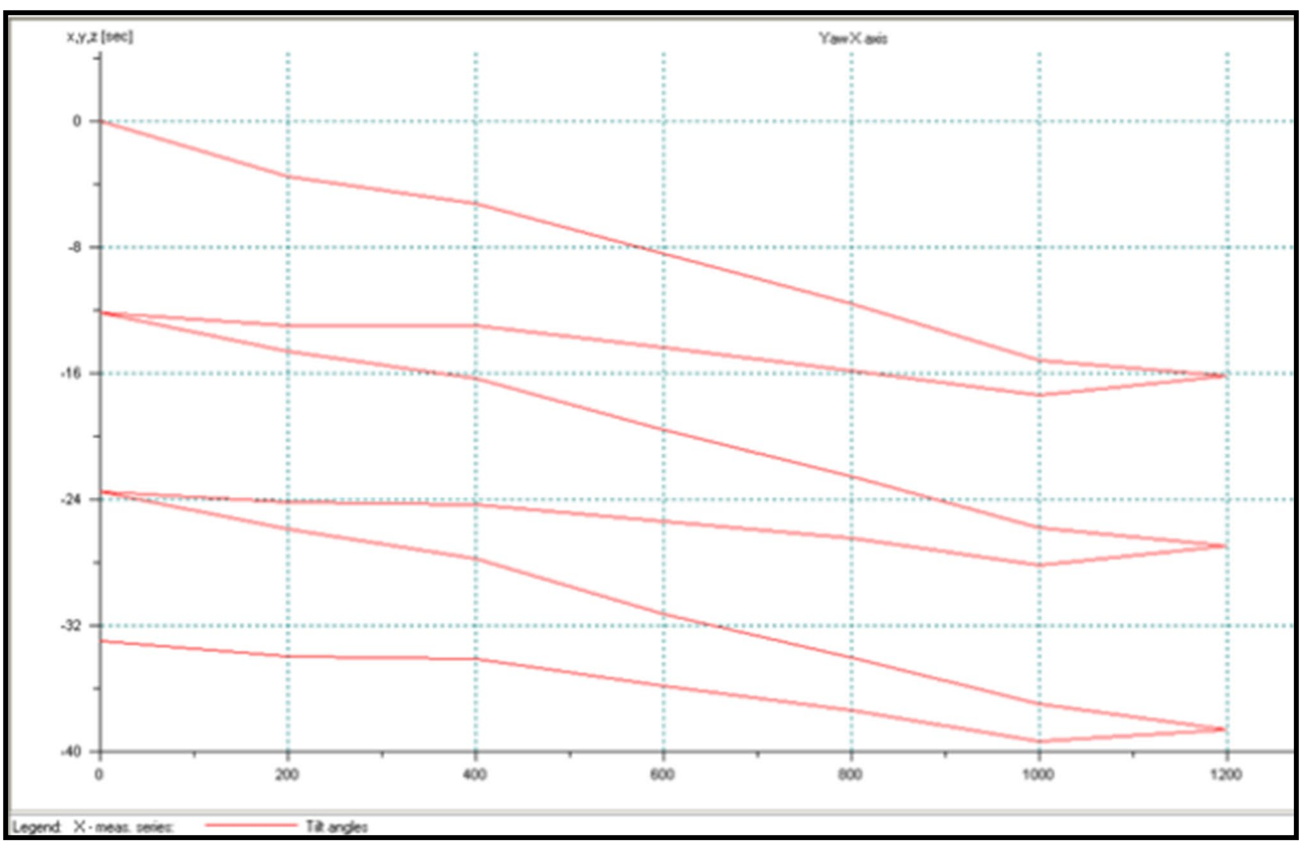

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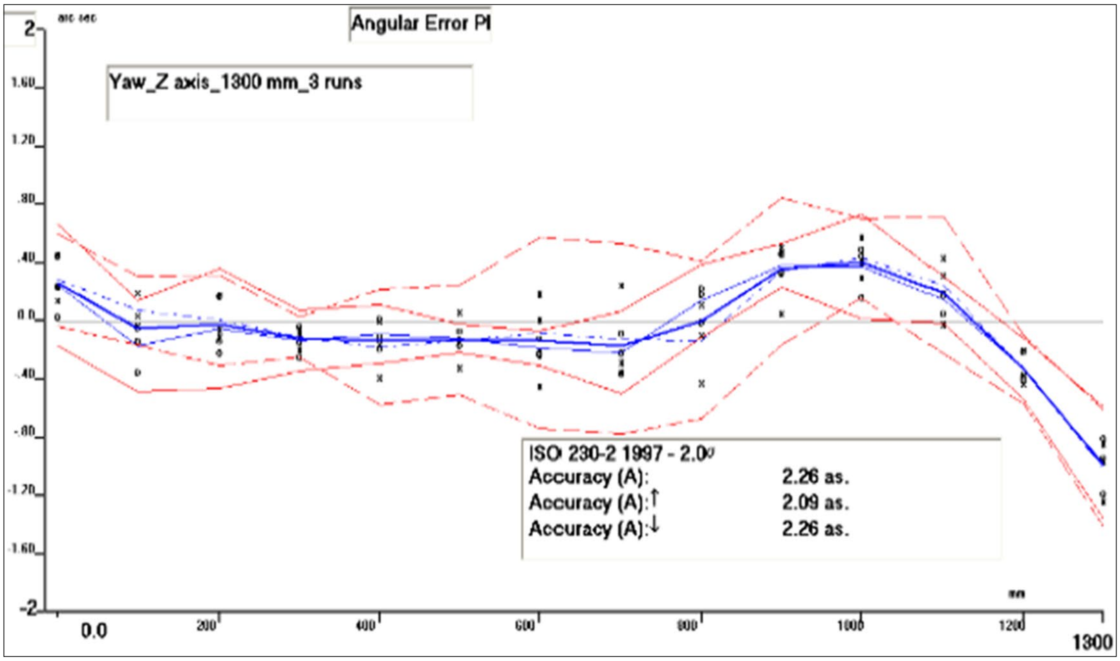
Fig. 15 Yaw measurements in *X* axis **a** laser interferometer, **b** autocollimator



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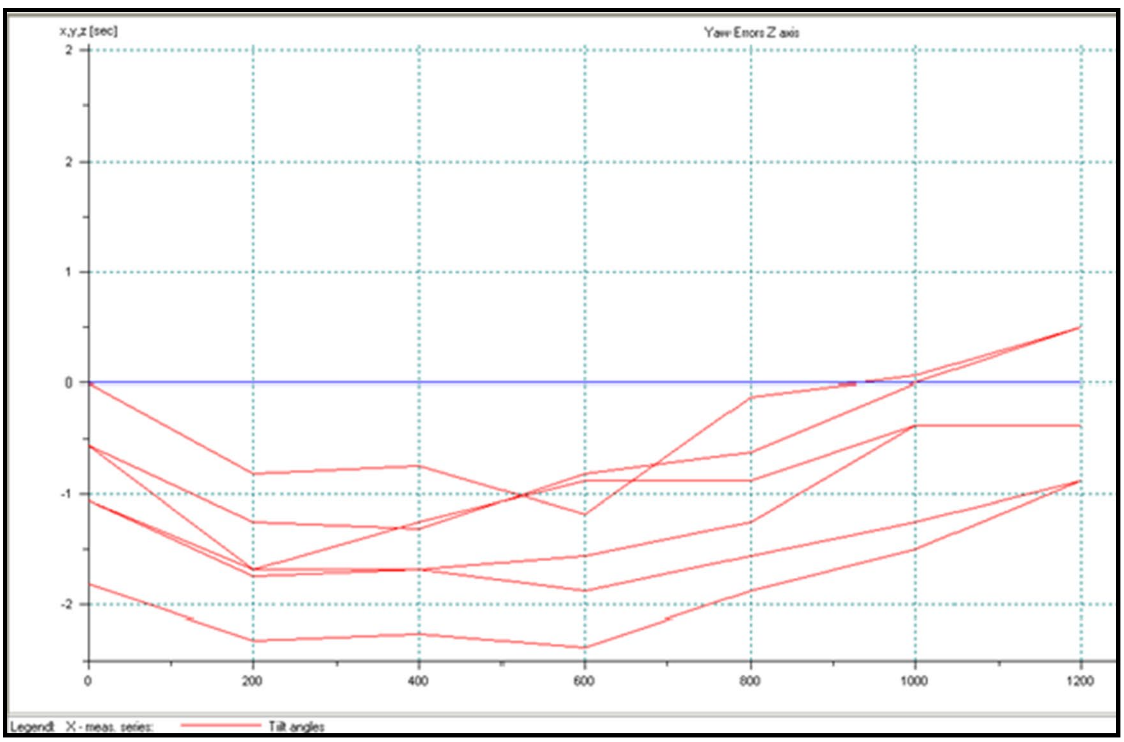

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Fig. 16 Yaw measurements in *Z* axis **a** laser interferometer, **b** autocollimator

Table 3 Straightness measurements in *X* axis

Measurand	Instrumentation	Straightness errors, μm
Horizontal straightness	Laser interferometer	40.52
	Autocollimator	10.91
	Straight edge	181
Vertical straightness	Laser interferometer	161.61
	Autocollimator	29.39
	Straight edge	164

Table 4 Straightness measurements in *Z* axis

Measurand	Instrumentation	Straightness errors, μm
Horizontal straightness	Laser interferometer	11.90
	Autocollimator	1.06
	Straight edge	28
Vertical straightness	Laser interferometer	7.76
	Autocollimator	0.58
	Straight edge	26

Although, there are previous research work in geometrical error determination of machine tools. The new issue in this work is that most of the errors are determined in one solid work. The most important thing also is the application of geometrical error determination for a CNC machine that used for the manufacturing of aircrafts parts. The manufacturing and re-machining processes of such parts require using high accurate CNC machine tools.

In this work, the geometrical errors of computerized numerical controlled (CNC) machine of vertical turning centering (VTC) type are comparatively determined, Fig. 2. The machine is composed of moving carriage in *X* and *Z* axes with multi-level (6 latches or positions) in Z direction, and rotary base. These geometrical errors are yaw, pitch, straightness, squareness, parallelism of carriage and spindle, and flatness of rotary base.

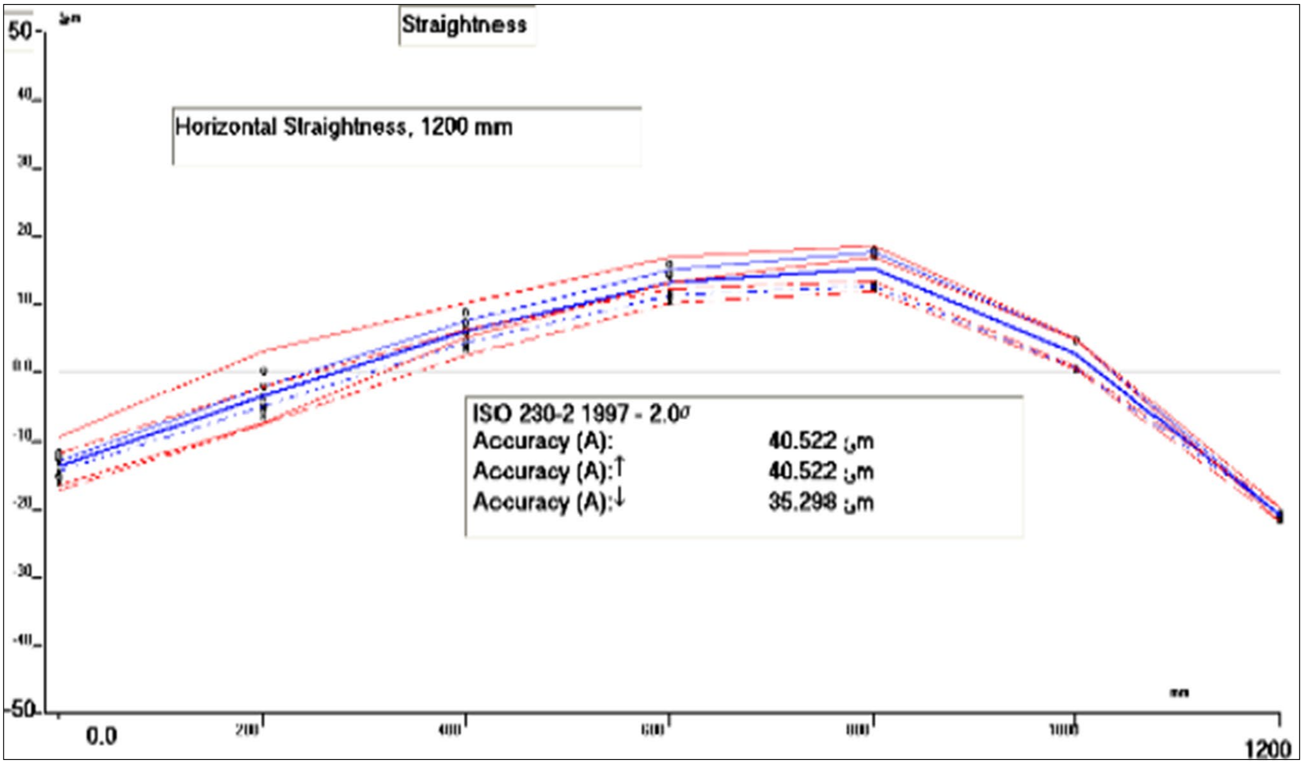
2 Methods and procedure

In this paper, two techniques of laser interferometer system and autocollimator system are used in determination of geometrical errors of machine tool. The laser interferometer system is a heterodyne type with 10 nm resolution, 5529A model and manufactured by Agilent — USA. The autocollimator system is of high-resolution type with 0.05 arc resolution, Elcomat 3000 model, and manufactured by Moeller-Wedel — Germany. There are some hand tools; precision dial gauges and long straight edge are also used.

2.1 Laser interferometer system

The laser interferometer system that was used in this study is working based on principle of displacement measurements using optical interference. It has in simply way one laser beam with two frequencies f_1 and f_2 splitted by the beam splitter into two; one beam (f_1) is moving arm “moveable cube corner reflector” and the other (f_2) is fixed arm “fixed cube corner reflector,” Fig. 3 [14, 15].

As the moving arm moves, a number of fringes are constructed. By multiplying the fringe number by half of the wave length of laser beam, the path difference between the two beams is calculated. This path difference represents the linear distance that the moveable arm is moved. This optical setup is used for linear measurements. For other measurement types, the types of optics and their setup are changed according to each experimental measurement application. In general, all measurements that can be done by laser interferometer system is based the determination of path difference between the two beams f_1 and f_2, Fig. 4. These measurements are angular measurements (yaw and pitch), straightness, squareness, parallelism, and flatness measurements.



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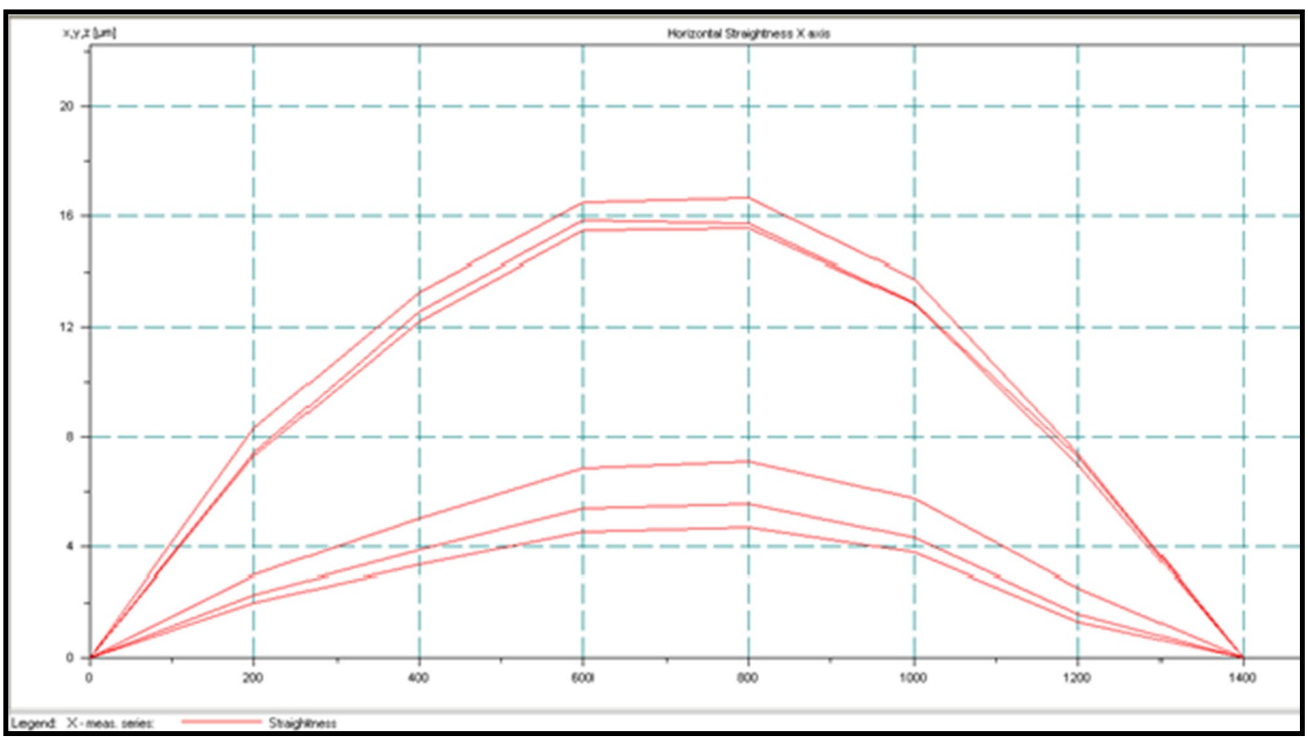

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Fig. 17 Horizontal straightness measurements in *X* axis **a** laser interferometer, **b** autocollimator

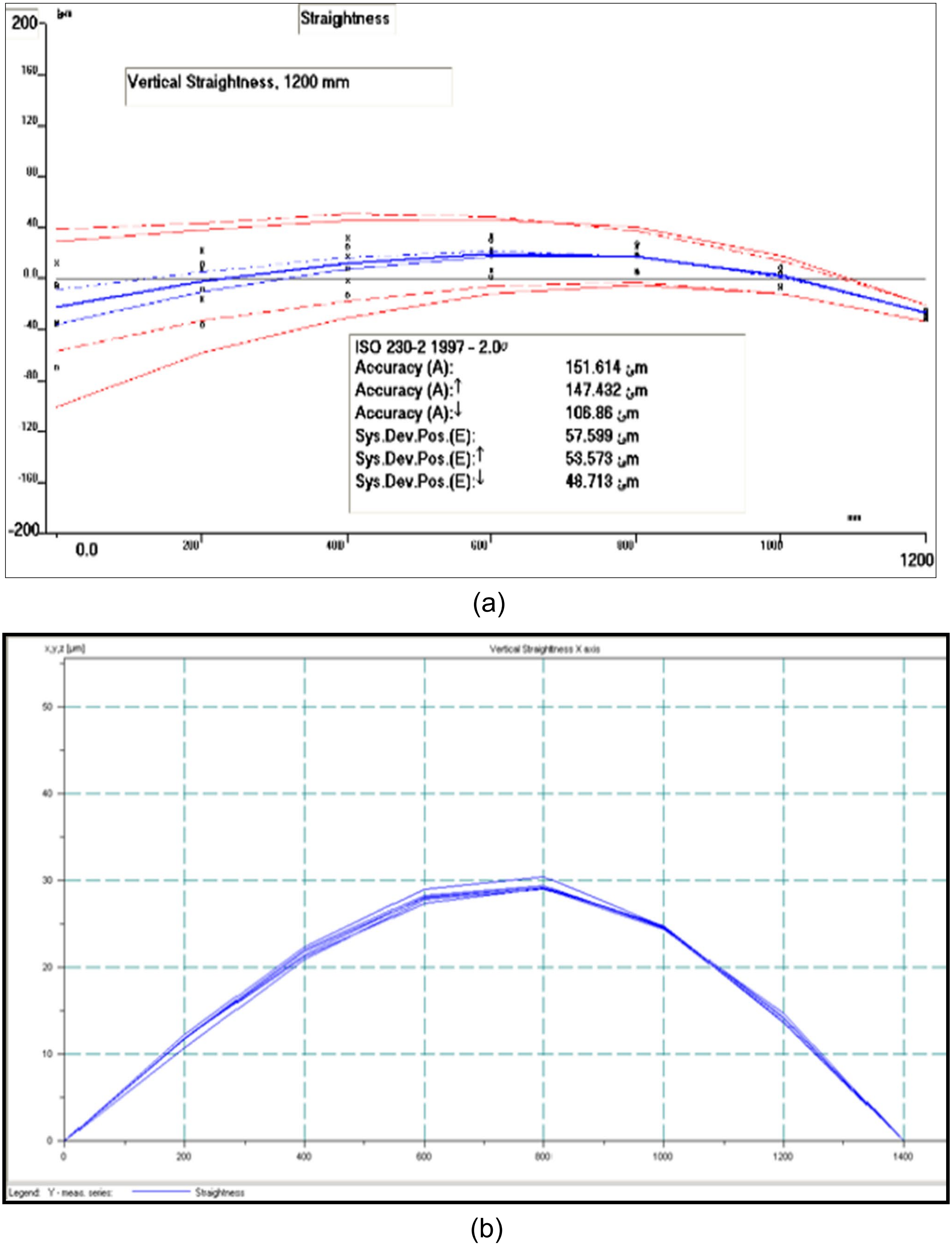
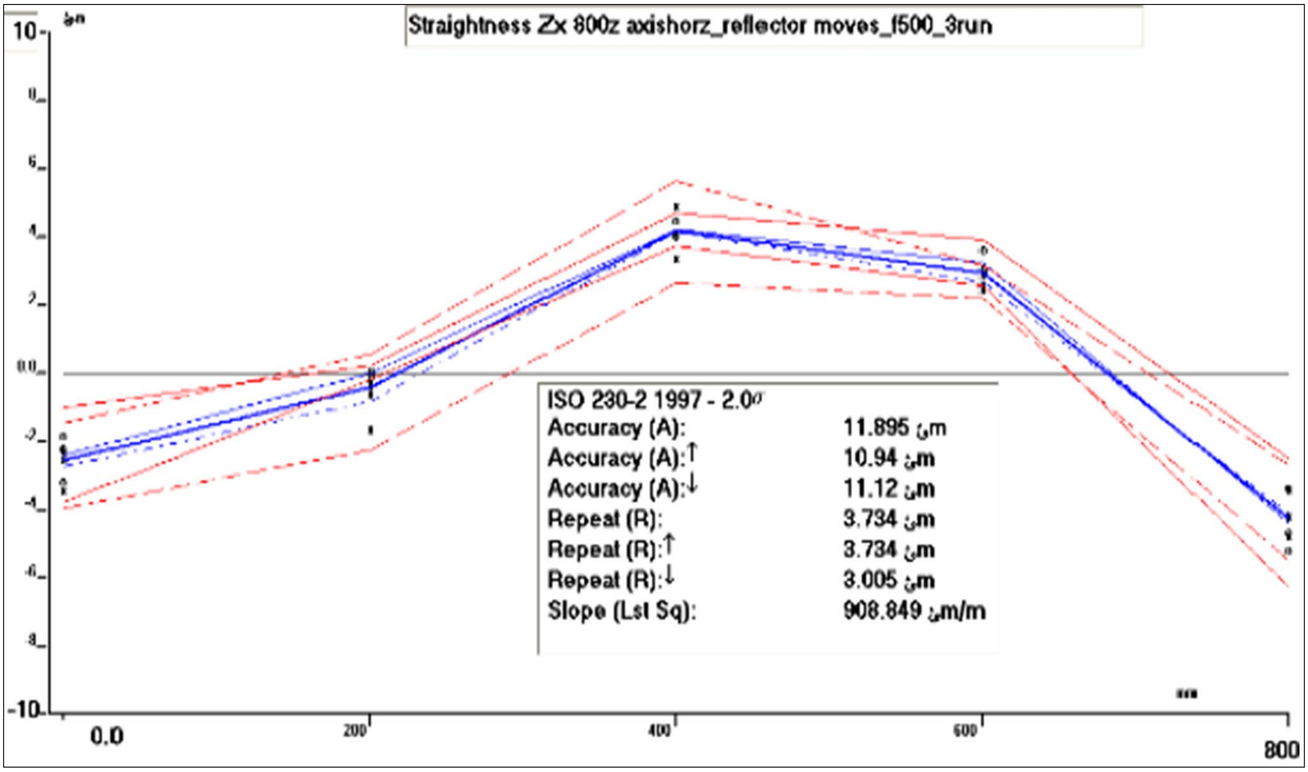


Fig. 18 Vertical straightness measurements in X axis **a** laser interferometer, **b** autocollimator



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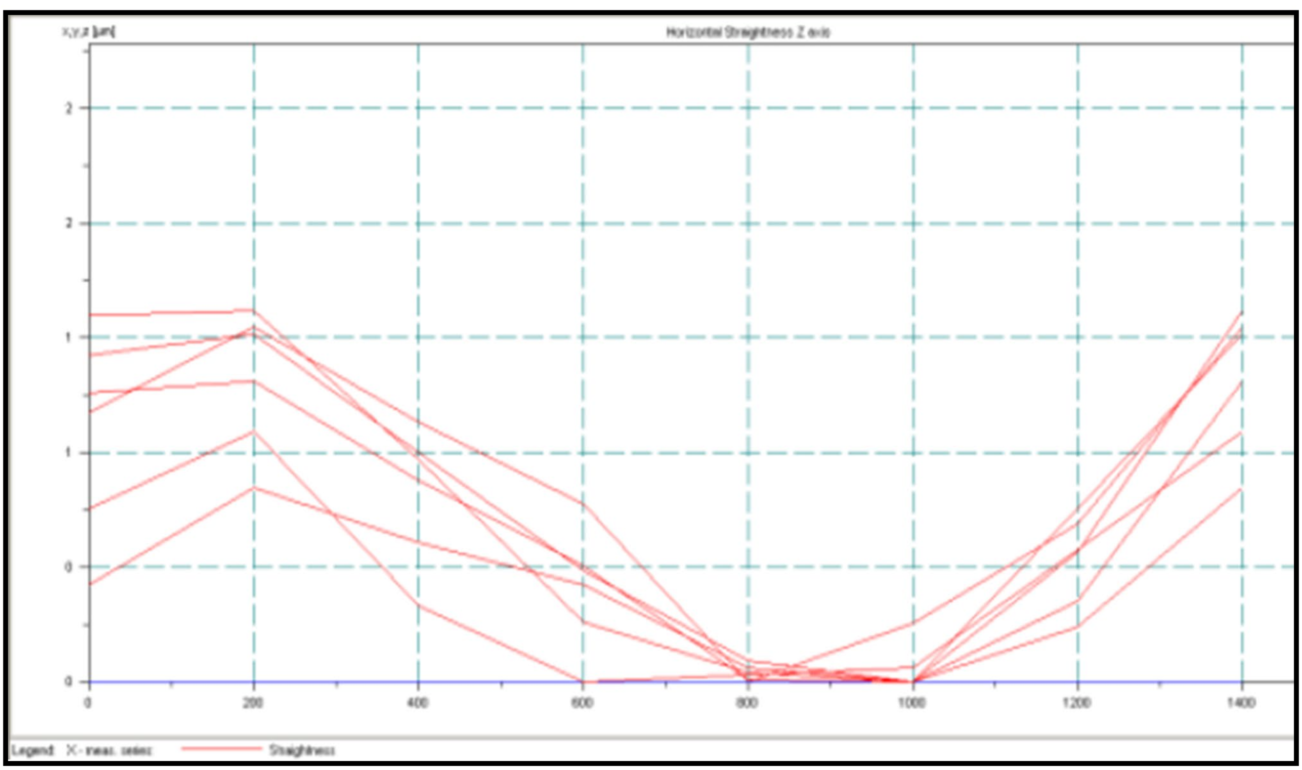

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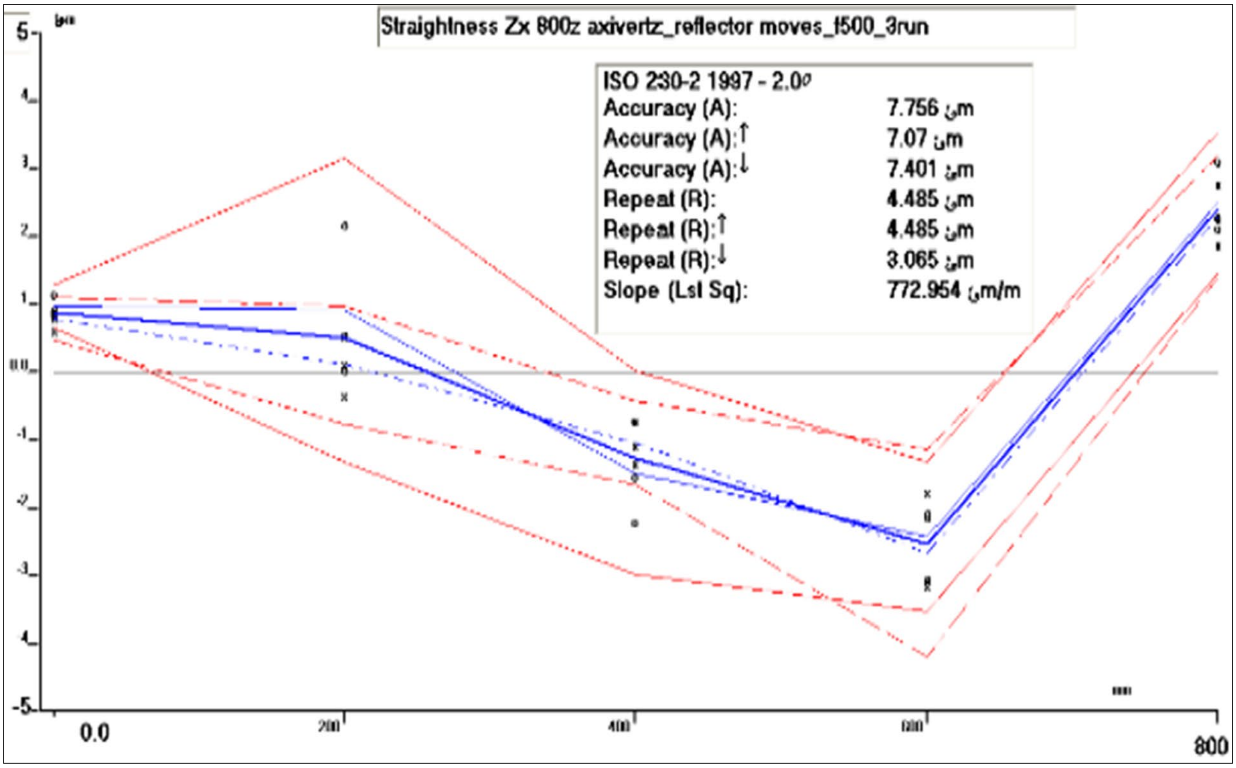
Fig. 19 Horizontal straightness measurements in *Z* axis **a** laser interferometer, **b** autocollimator



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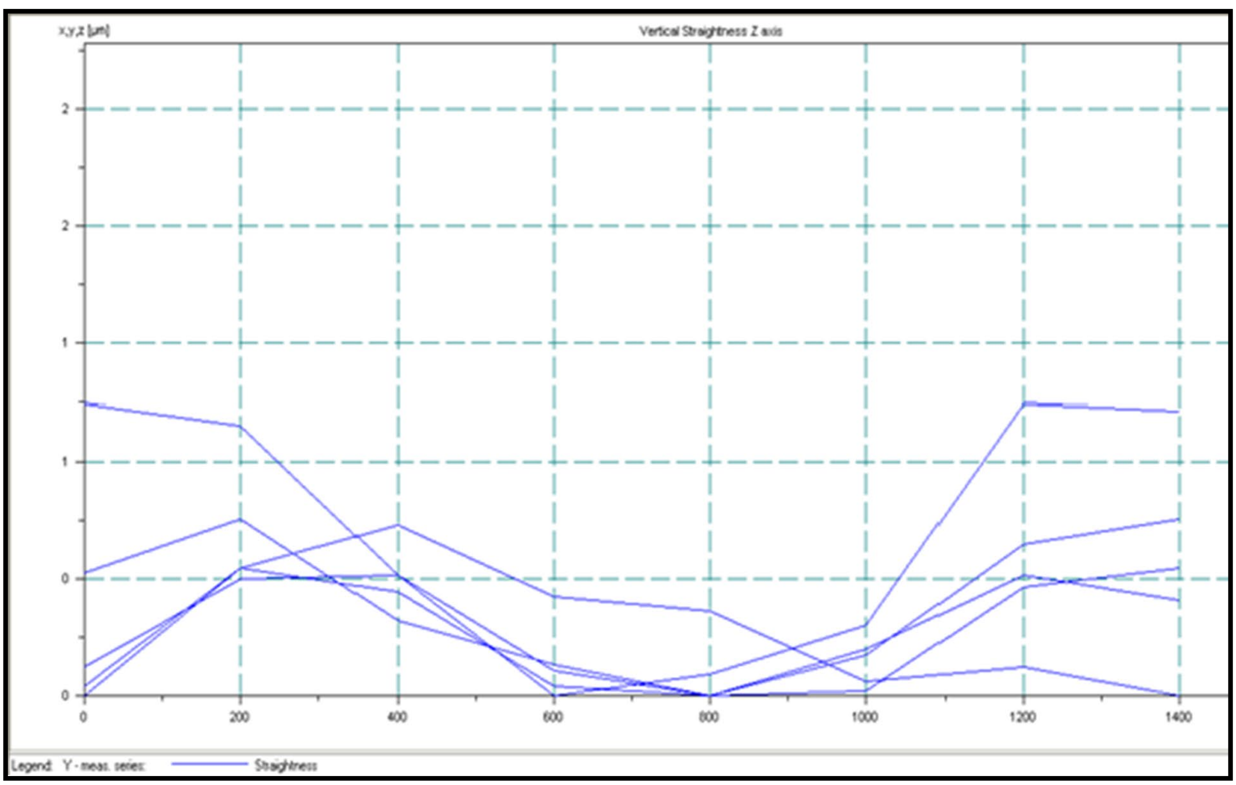


(b)

Fig. 20 Vertical straightness measurements in Z axis **a** laser interferometer, **b** autocollimator

Table 5 Squareness measurements

Axis	Instrumentation	Squareness errors, arcs
XZ axes	Laser interferometer	−0.003
	Autocollimator	−8.28
	Straight edge	2.4

Practical setups for measurements of angular errors (yaw and pitch), straightness, squareness, and flatness measurements are shown in Figs. 5, 6, 7, and 8 respectively.

2.2 Autocollimator system

The autocollimator is an optical instrument which measures angular displacements of a mirror or other suitable reflecting surfaces. It is mainly designed to measure small angles [16]. The image of an illuminated object, located in the rear focal plane of the collimator lens, is projected to infinity and reflected via a mirror, as in Fig. 9.

The image is picked up by a light sensitive receiver. A slight alteration of the angle between the optical axis of the autocollimator and the mirror causes a deviation which can be determined very precisely. The electronic autocollimator type provides measurement of smallest deviation of inclination in two orthogonal axes in fractions of arc seconds. This optical design of autocollimator can be used for measurements of angular errors (yaw and pitch), straightness, squareness, parallelism and flatness, Figs. 10, 11, and 12.

2.3 Hand tools

Some simple tools and standards are used in determination of errors of the machine. These are dial indicator and straight edge. The straight edge is used in the determination of straightness, parallelism, and squareness of the machine as shown in Fig. 10. The dial is inserted in the tool position and touches the edge along its length in different orientation.

3 Experimental results

Five types of geometrical errors of the VTC CNC machine are measured. These errors are angular errors, straightness, squareness, parallelism, and flatness errors.

3.1 Angular errors

The angular errors of pitch and yaw errors are measured for moving range of machine. One setup of autocollimator system is used to measure pitch and yaw errors in the same time. The laser interferometer system measures these two error types individually where the optical elements are oriented one time in horizontal position and once more in vertical position. The angular errors are measured in arc second (arcs) unit for both axes X and Z. The results for angular measurements are presented in Tables 1 and 2 and Figs. 13, 14, 15, and 16.

3.2 Straightness measurements

The out of straightness for moving spindle is measured. This geometric property is measured for horizontal and vertical straightness. Also, one setup of autocollimator system is used to measure straightness errors in the same time. The laser interferometer system measures these error types individually where the optical elements are oriented, one time is horizontal position, and once more in vertical position. The horizontal and vertical straightness errors are measured for both axes X and Z. The results for straightness measurements are presented in Tables 3 and 4 and Figs. 17, 18, 19, and 20.

3.3 Squareness measurements

The out of squareness for moving spindle is measured. This geometric property is measured between X axis and Z axis. The autocollimator system is used to measure straightness in X axis and then the straightness is measured in Z axis. The laser interferometer system measures these error type individually where the optical elements are oriented one time in horizontal position and once more in vertical position. The squareness errors are measured by both instruments in addition to straight edge. The results for squareness measurements are presented in Table 5 and Fig. 21.

3.4 Parallelism measurements

The out of parallelism for moving spindle is measured. This geometric property is measured for both of X axis and Z axis. The laser interferometer system and Autocollimator System are used to measure straightness in X axis and then the straightness is measured in X' axis. The same

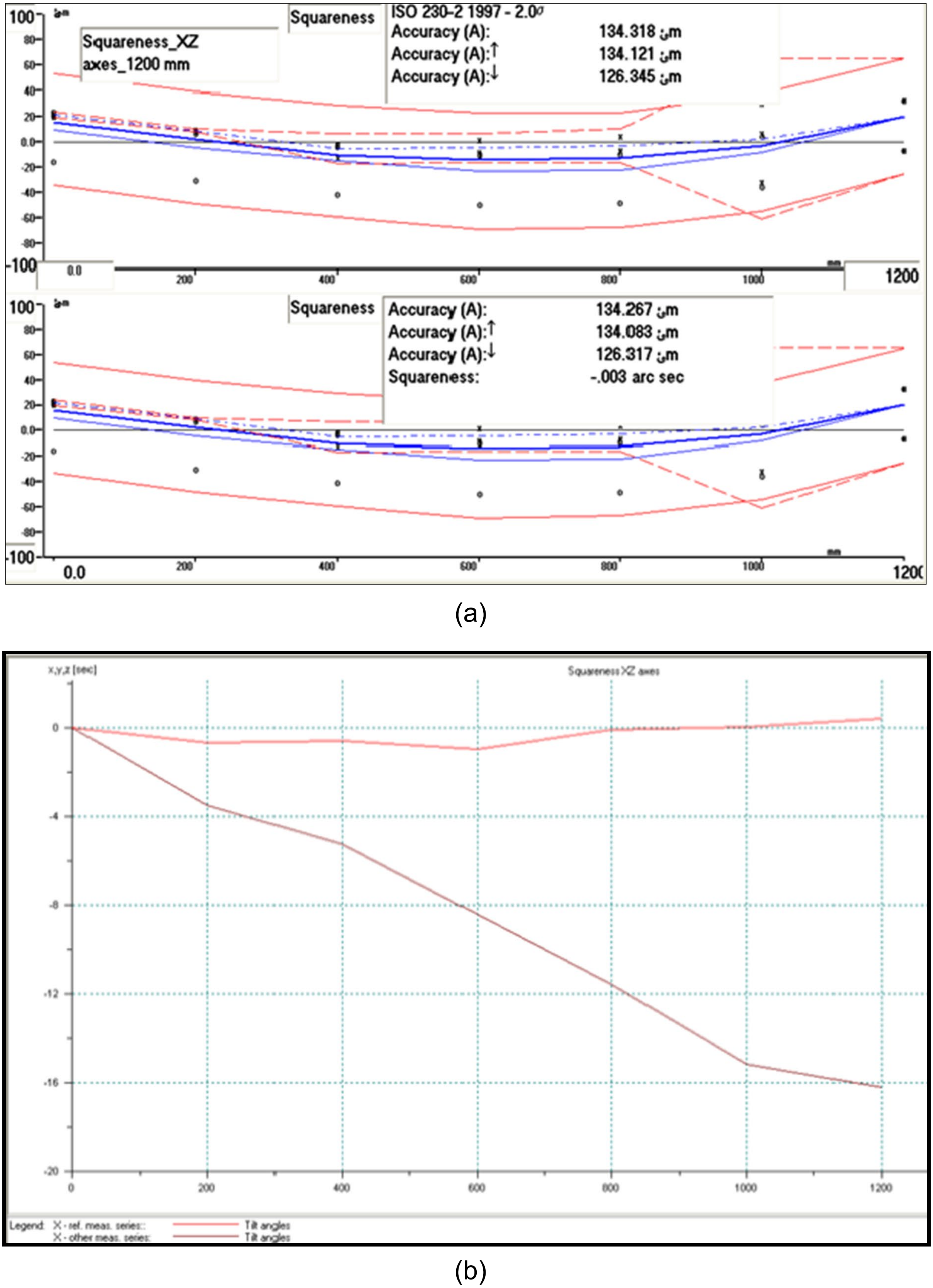


Fig. 21 Squareness measurements **a** laser interferometer and **b** autocollimator

Table 6 Parallelism measurements

Axis	Instrumentation	Errors, arcs
X axis	Laser interferometer	−166.415
	Autocollimator	0.50
	Straight edge	3.1
Z axis	Laser interferometer	−21.582
	Autocollimator	−0.32
	Straight edge	0.66

measurements are repeated for *Z* axis. From two straightness measurements at each axis, the out of parallelism is determined. The parallelism errors are measured by both instruments in addition to straight edge. The results for parallelism measurements are presented in Table 6 and Figs. 22 and 23.

3.5 Flatness measurements

The rotary base plate is calibrated for its out of flatness based on Union-Jack method, Fig. 24. Eight generators (lines) are used as guides for measurement of heights at spaced-points by 100 mm (4 inches). The plate is calibrated by both laser and autocollimator systems, Table 7 and Fig. 25.

4 Discussion

4.1 Angular errors

The measurements of angular errors in *X* axis are ranged from 26.6 to 29.56 arcs for pitch measurements and 10.4 to 32.56 arcs for yaw measurements. It appears a difference between laser interferometer and autocollimator for pitch measurements ~ 3 arcs and ~ 22 arcs for yaw measurements. As in Fig. 26a, the measurement results give a difference about 3 arcs between laser interferometer and autocollimator which represent ~ 10% difference less for autocollimator. In Fig. 26b, the results by autocollimator are about the third value of the results by laser interferometer. In some cases, the complicated optical setup of laser system allows the reasons for rising errors in measurements for the machine under test.

For *Z* axis, the measurements of angular errors are ranged from 0.8 to 4.21 arcs for pitch measurements and 1.2 to 2.26 arcs for yaw measurements. As in Fig. 27 a and b, the measurement results by autocollimator represent about 20% and 50% of the measurement results by laser interferometer for pitch and yaw measurements respectively. This shows an advantage for using of autocollimator in comparison to laser interferometer in this kind of measurements.

4.2 Straightness errors

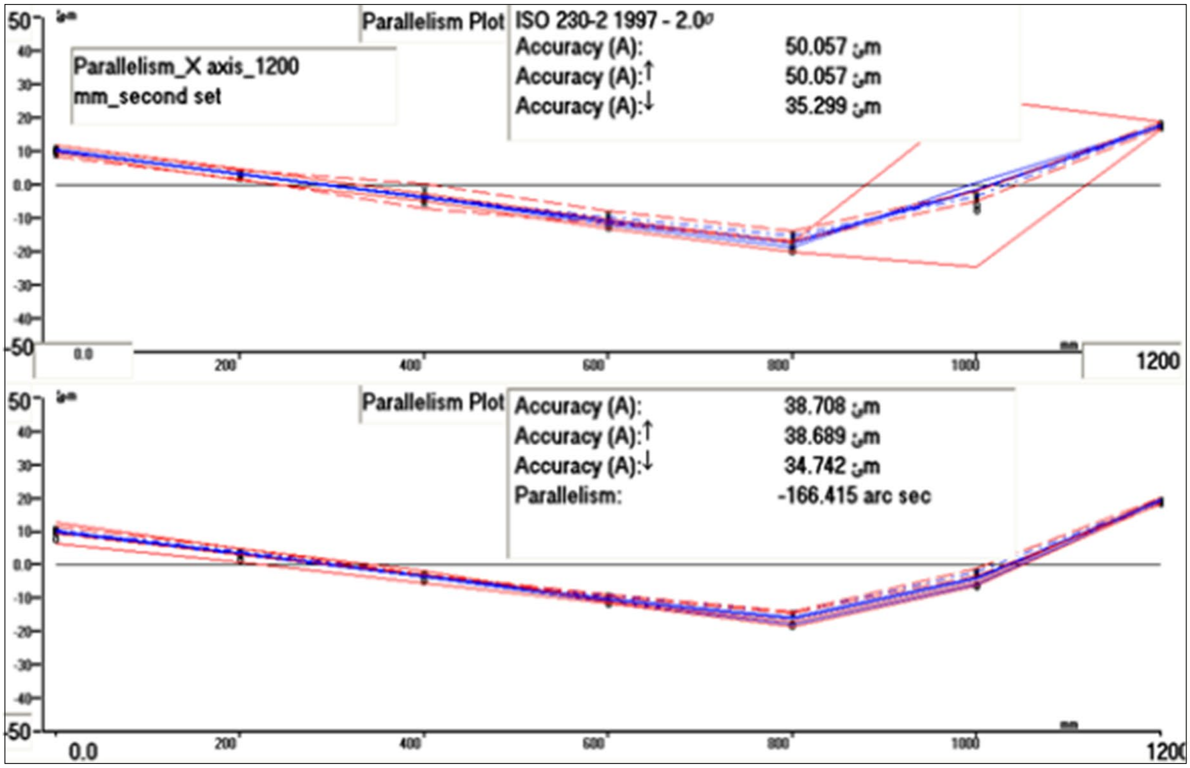
The measurements of straightness errors resulted in lower values by autocollimator in comparison to either laser interferometer or straight edge.

For *X* axis, the measurement results for horizontal straightness are 10.91 µm by autocollimator, 40.52 µm by laser interferometer, and 181 µm by straight edge. The measured straightness errors by autocollimator are about 25% and 5% of that by laser interferometer and straight edge respectively. The vertical straightness measurements in *X* axis resulted in straightness errors of 29.39 µm by autocollimator, 161.61 µm by laser interferometer and 164 µm by straight edge, Fig. 28 a and b. The measured straightness errors by autocollimator are about 20% of that by either laser interferometer or straight edge.

For *Z* axis, the horizontal straightness measurements give straightness errors of 1.06 µm by autocollimator, 11.9 µm by laser interferometer, and 28 µm by straight edge. The measured straightness errors by autocollimator are about 5% and 10% of that by laser interferometer and straight edge respectively. The straightness errors for vertical straightness measurements are 0.58 µm by autocollimator, 7.76 µm by laser interferometer, and 26 µm by straight edge, Fig. 29. The measured straightness errors by autocollimator are about 2% and 8% of that by laser interferometer and straight edge respectively.

4.3 Squareness errors

The measurements of squareness errors resulted in lower values by laser interferometer in comparison to either autocollimator or straight edge. It is −0.003 arcs by laser interferometer, −8.28 arcs by autocollimator, and 2.4 arcs by straight edge, Fig. 30. The measured squareness errors by laser interferometer are about 0.05% and 0.2% of that by autocollimator



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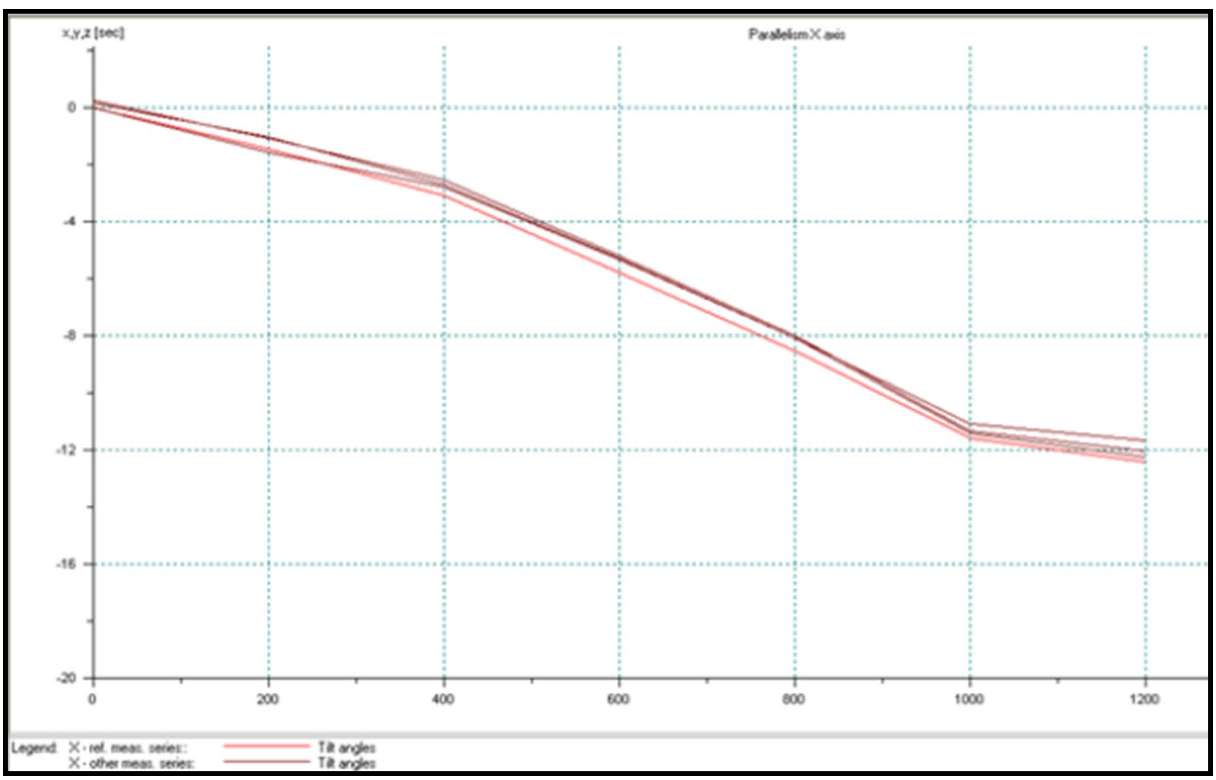

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Fig. 22 Parallelism measurements in *X* axis **a** laser interferometer, **b** autocollimator

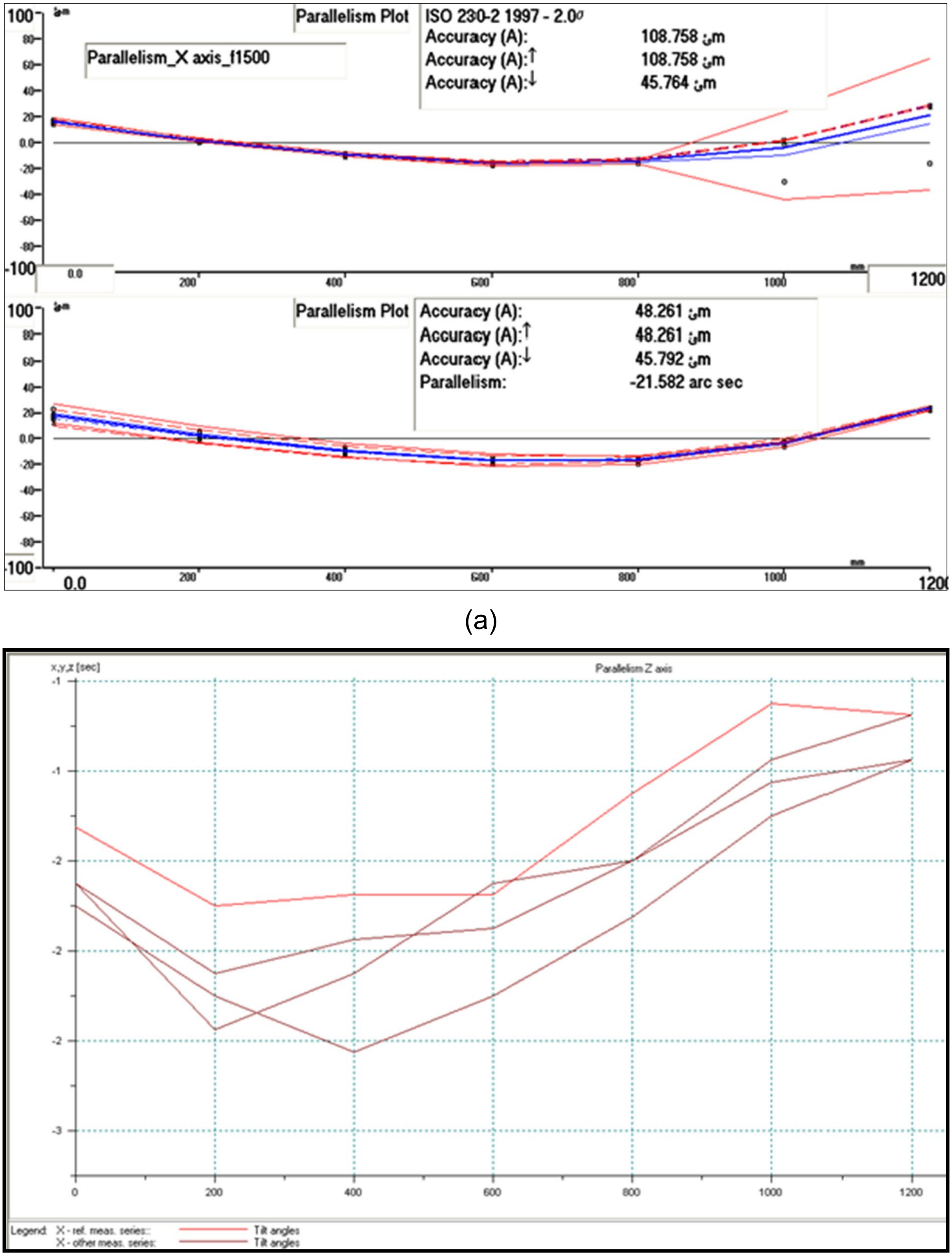


Fig. 23 Parallelism measurements in *Z* axis **a** laser interferometer, **b** autocollimator

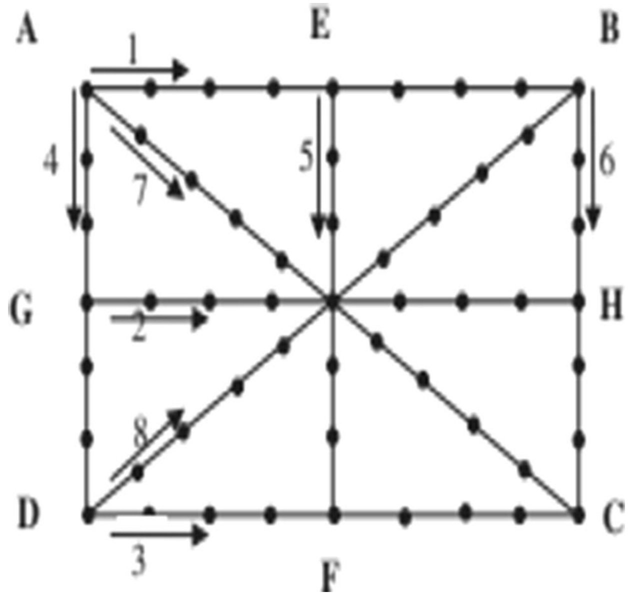


Fig. 24 Union-Jack method

Table 7 Flatness measurements Plot of CNC rotary base plate

Measurand	Instrumentation	Flatness deviation, µm
Rotary base plate	Laser interferometer	112.38
	Autocollimator	100.14

and straight edge respectively. The laser interferometer has especially at this type of measurements one fixed setup for the laser head and beam splitter; this may improve the squareness measurements by laser interferometer.

4.4 Parallelism errors

The measurements of parallelism errors resulted in lower values by autocollimator in comparison to either laser interferometer or straight edge. It is 0.5 arcs by autocollimator, – 166.415 arcs by laser interferometer, and 3.1 arcs by straight edge in X axis. For Z axis, it is – 0.32 arcs for autocollimator, – 21.582 arcs by laser interferometer, and 0.66 arcs by straight edge, Fig. 31. This shows an advantage for using of autocollimator in comparison to laser interferometer and straight edge in this kind of measurements.

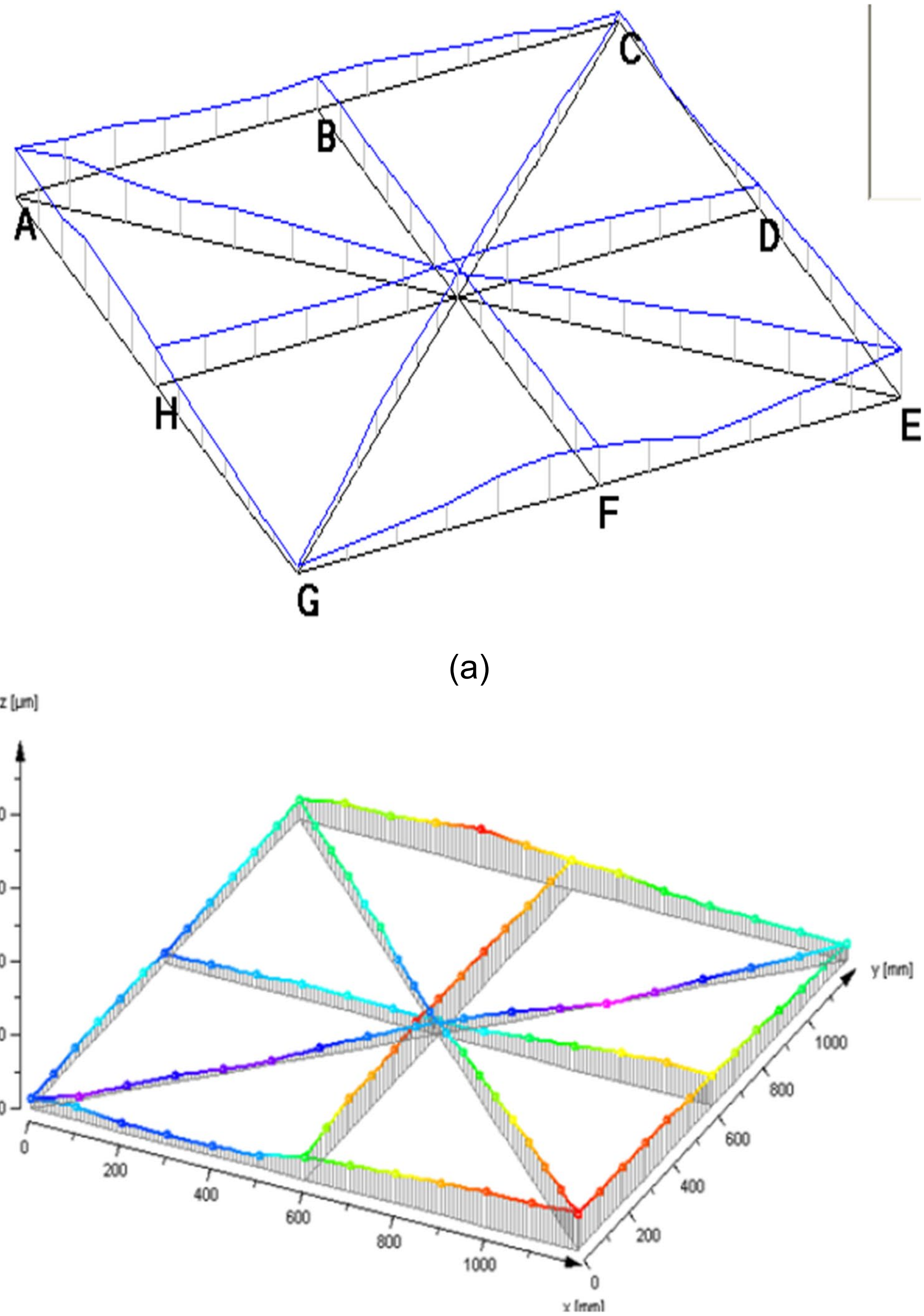
4.5 Flatness errors

The measurements of flatness deviations of machine rotary base resulted in lower values by autocollimator in comparison to laser interferometer about 10% less. It is 100.14 µm by autocollimator, 112.38 µm by laser interferometer, Fig. 32. This difference may be due to foot spacer distance for the mirror carriage of reflected mirror for autocollimator (100 mm). For laser interferometer, it is 4 inches (101.4 mm). This 1.4 mm may cause in this 10% difference in results.

5 Conclusions

The geometric errors of angular errors (pitch and yaw), horizontal straightness, vertical straightness, squareness, parallelism, and flatness deviations are measured. The measuring instruments of autocollimator and laser interferometer are used in all measurement types. A standard straight edge is used in some measurements, straightness, squareness, and parallelism. The measurements by autocollimator resulted in clear difference of the measured errors in comparison to laser interferometer in all types except at squareness measurements. The complicated optics setup for laser interferometer in some measurement types may add some additional errors sources that propagate the measured errors. Even though, laser interferometer is still powerful and precise measuring instrument in calibration of CNC machines. The straight edge is capable to be used in straightness, squareness, and parallelism measurements. It gives an easy portable tool in quick assessment of machine tools.

Fig. 25 Flatness measurements Plot of CNC rotary base plate, **a** laser interferometer and **b** autocollimator



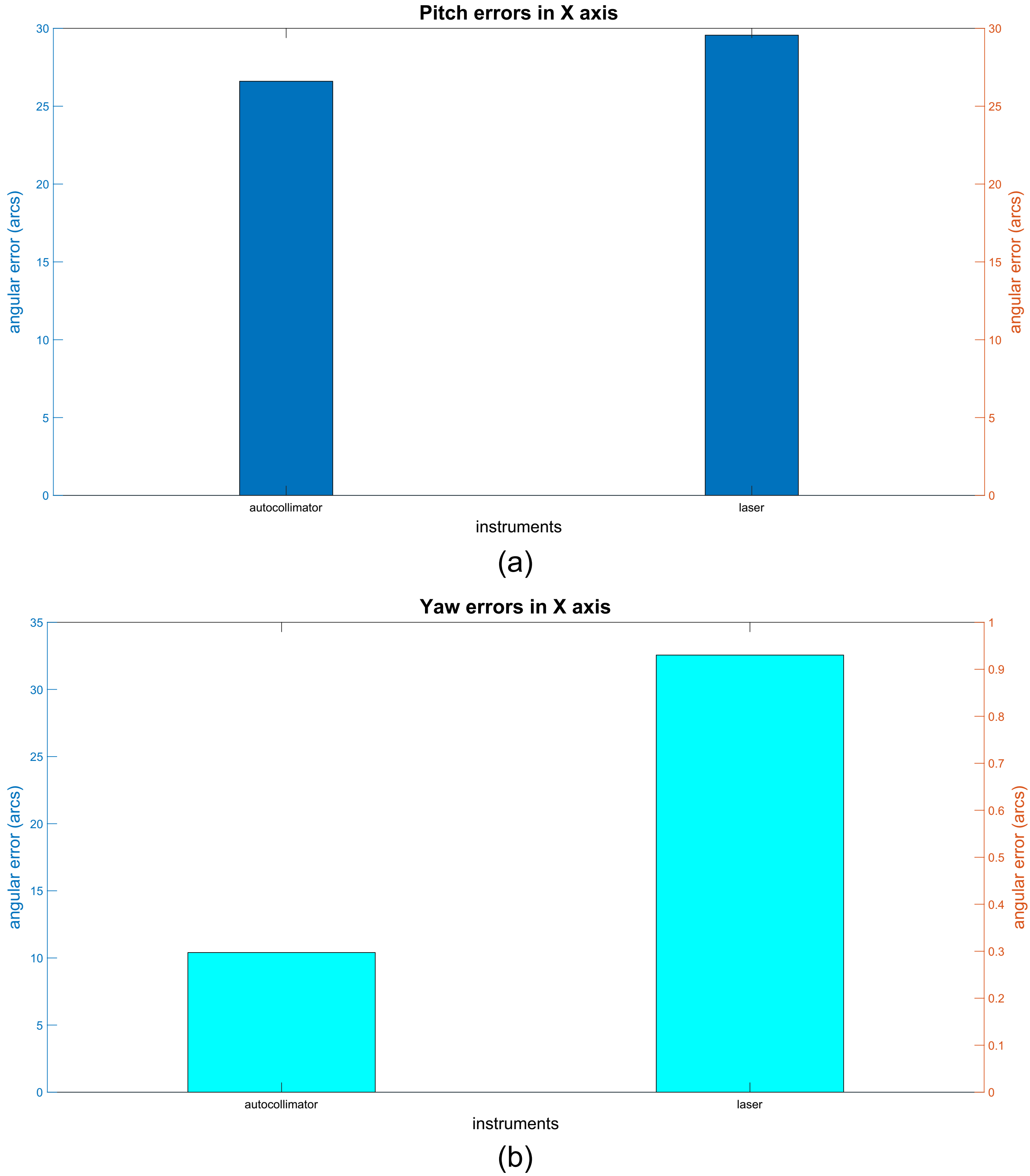


Fig. 26 Angular errors in X axis, **a** pitch and **b** yaw

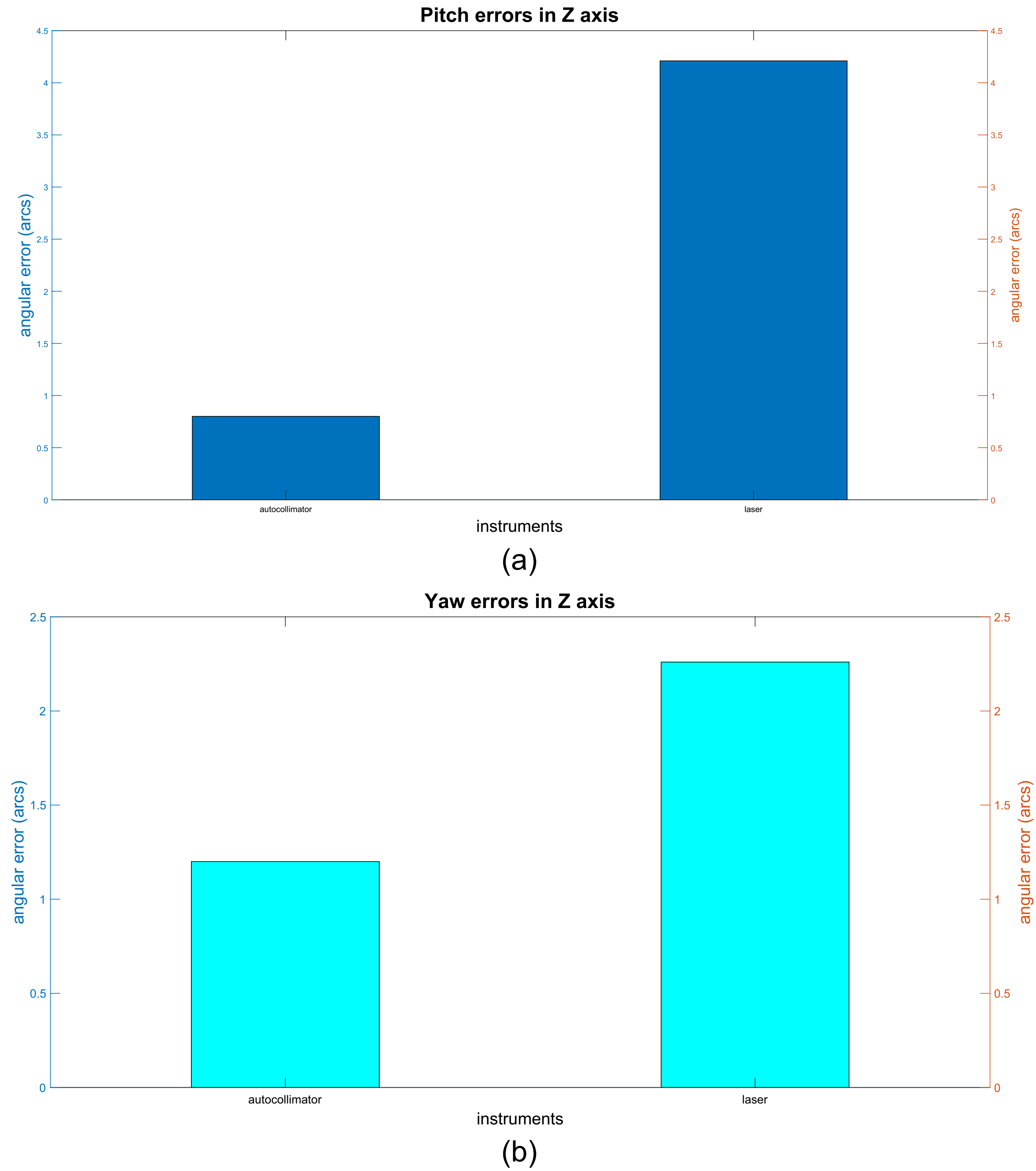


Fig. 27 Angular errors in Z axis, (**a**) pitch and (**b**) yaw

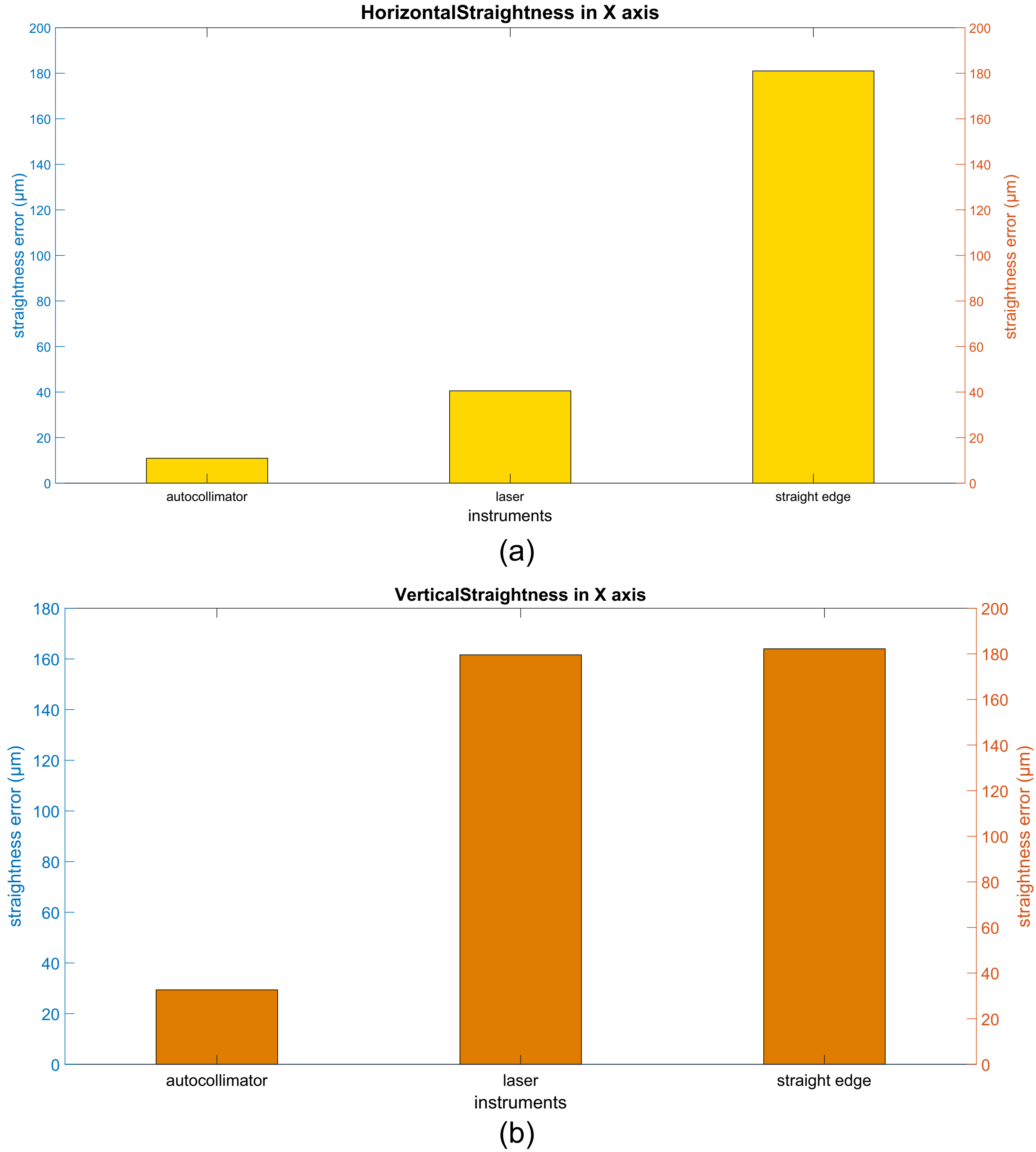


Fig. 28 straightness errors in X axis, **a** horizontal and **b** vertical

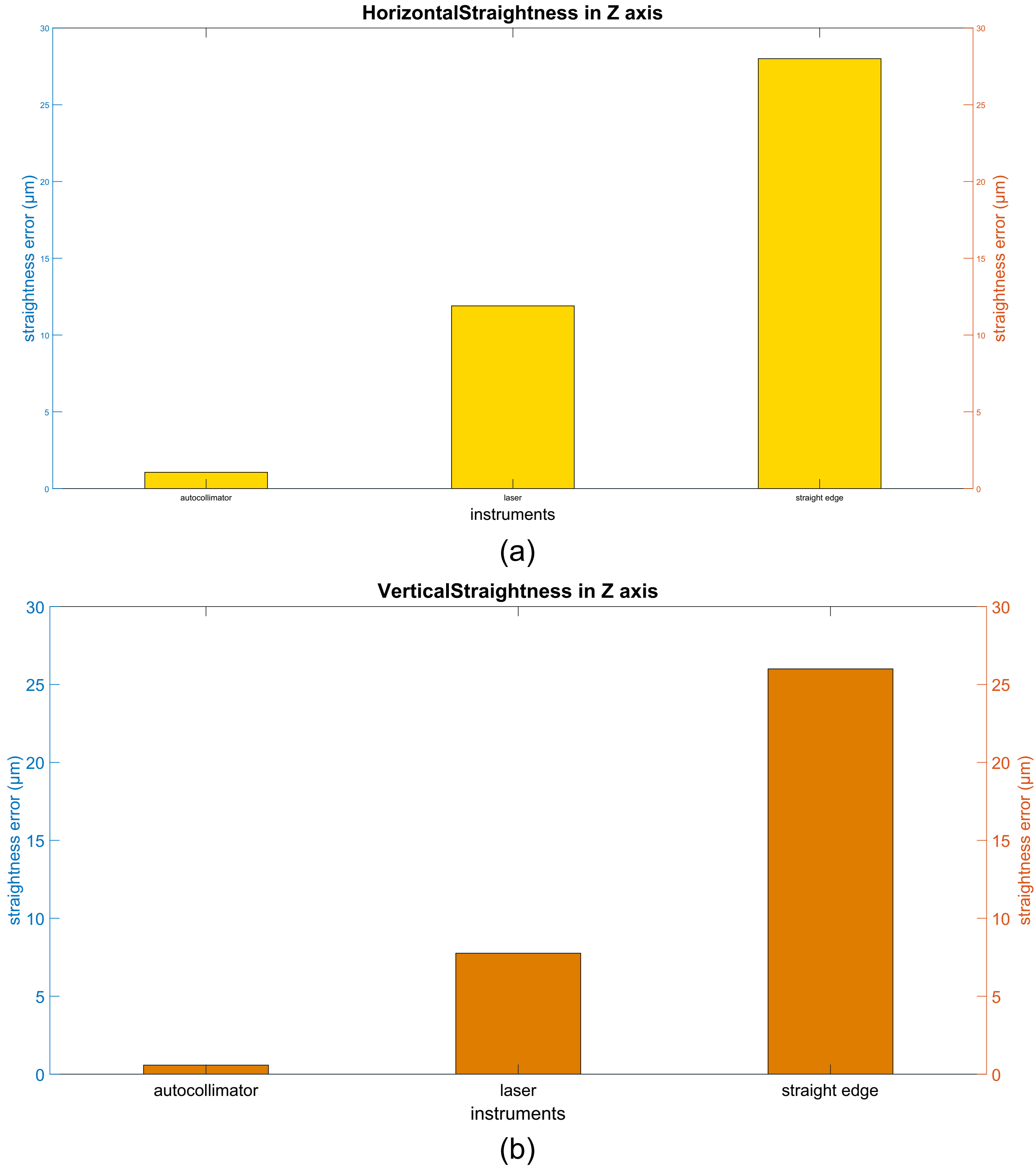


Fig. 29 Straightness errors in *Z* axis, **a** horizontal and **b** vertical

Fig. 30 Squareness errors in *XZ* axes

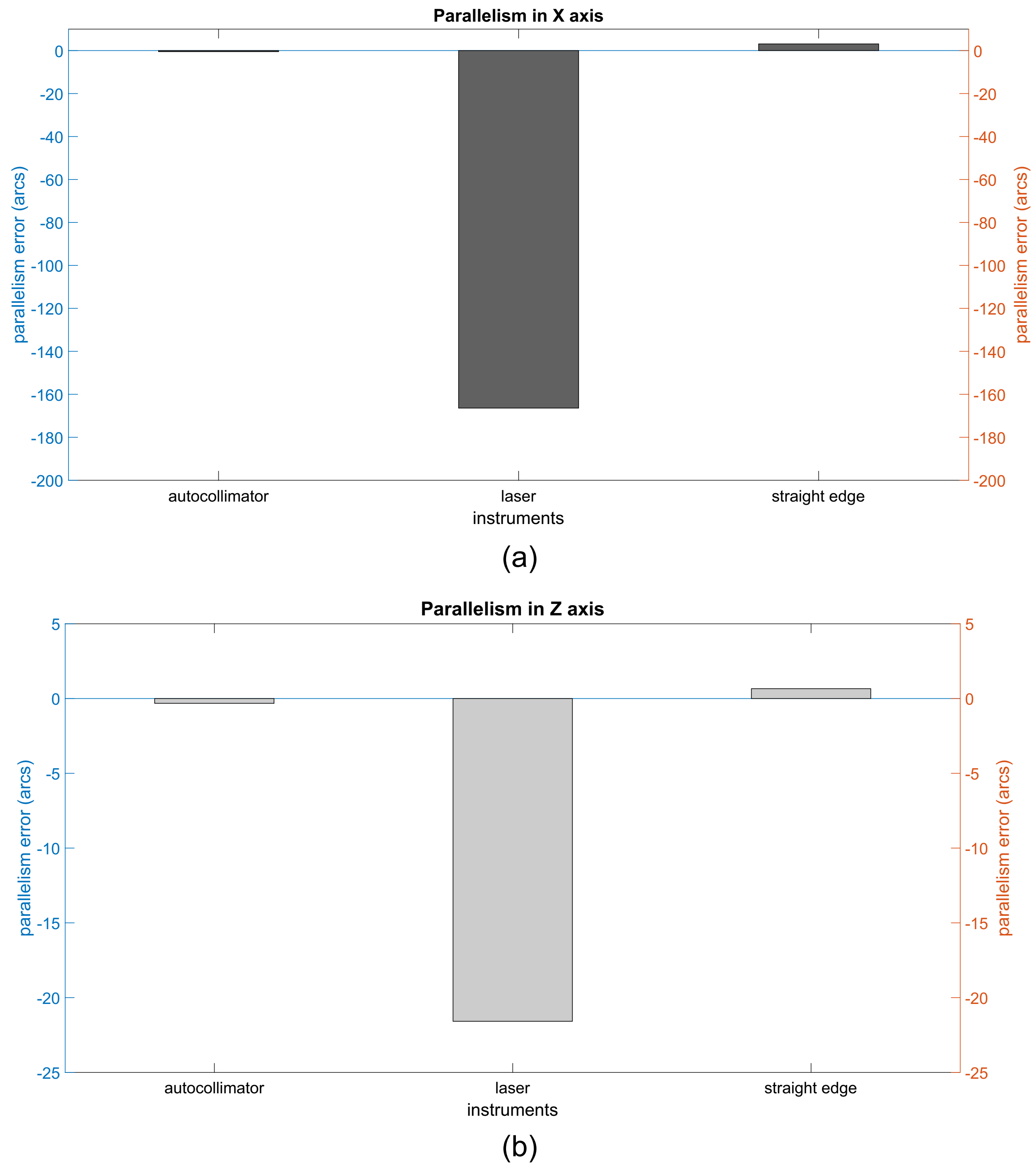


Fig. 31 Parallelism errors, **a** *X* axis and **b** *Z* axis

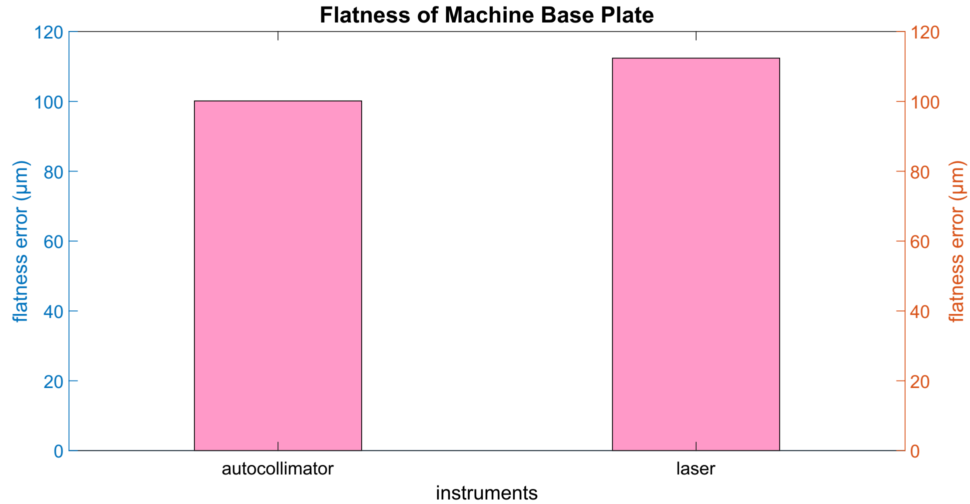


Fig. 32 Flatness errors

Abbreviations CNC machine: Computerized numerical controlled machine; CCD camera: Charged-coupled device camera; VTC machine: Vertical turning-center machine; arcs: Arc second

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Declarations

Competing interests The authors declare no competing interests.

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