LASER INTERFEROMETRY – MEASUREMENT AND CALIBRATION METHOD FOR MACHINE TOOLS

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ABSTRACT
One of the way for a very accurate control of the geometric accuracy of machine tools (conventionally and CNC controlled) is to use interferometry measurement methods. Laboratory for metal cutting and machine tools (Loram) at Faculty of Mechanical Engineering, University of Zenica has several devices to control the accuracy of machine tools.
This paper presents the results of some accuracy measurements of machine tools using Ranishaw ML10 laser system. These are measurement results of CNC lathe (deviation from linear motion), CNC milling machine (dynamic behaviour), deep drilling machine (straightness), CNC milling machine (comparative measurement straightness according to two different methods of measurement: interferometry and CCD method).

Keywords: Machine Tools, Accuracy, Laser Interferometry

1. INTRODUCTION

One of the most important activities related to the maintenance of the machine tool is periodically checking the geometric and kinematics accuracy of machine tools. Static and dynamic stiffness of machine tools is one of the basic prerequisites for the proper operation of the machine tools. Measurements of certain parameter accuracy of machine tools in the appropriate time of period, provide the information needed to define the static and dynamic stiffness of machine tools. On the other hand, the measurement of geometric deviations such as straightness, parallelism, flatness and so on, giving the ability to assess the level of accuracy that is specific machine tools can be used. In practice, several methods are available for checking and testing geometric and kinematics accuracy of machine tools. One of the most accurate and efficient method is the interference of light. The use of light interference principles as a measurement tool goes back to the 1880s when Albert Michelson developed interferometry. The Michelson interfero-meter consists of a light source of a single wavelength (monochromatic), a half silvered mirror and two mirrors, as shown in Figure 1. The light source is split at the surface of the half silvered mirror, half the light being reflected through 90° towards a fixed distance mirror, the remaining half being allowed to pass through to a moveable mirror. The mirrors are aligned so that the recombined beams reflected from the mirrors are parallel and are reflected back towards an observer. If each of the mirrors is exactly the same distance from the half mirror, then the light will arrive at the observer in phase and constructive interference will occur, resulting in bright light. If the moveable mirror is positioned further away so that its position is shifted by one quarter wavelength, then the beam will return to the observer 180° out of phase and destructive interference will occur, resulting in darkness. Therefore, the distance moved by the moveable mirror can be measured by the observer counting the flashes of light as the mirror moves.

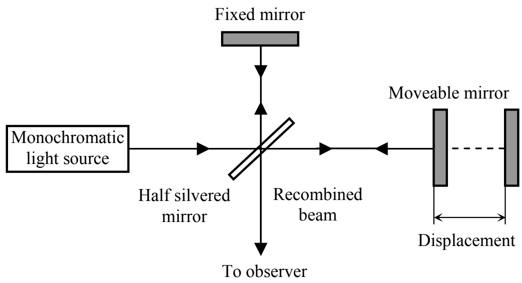

Figure 1. Basic Michelson interferometer

When the two light waveforms of the same wavelength are in phase, that is when the wave peaks coincide as shown in Figure 2.a, the result is known as „constructive interference". In constructive interference the amplitude of the output wave is equal to the sum of the amplitudes of the two input waves. When the two coherent light waveforms are 180° out of phase, that is when the peak of one input coincides with a trough of the other as shown in Figure 2.b, the result is known as „destructive interference". In destructive interference the two input waves cancel one another resulting in darkness.

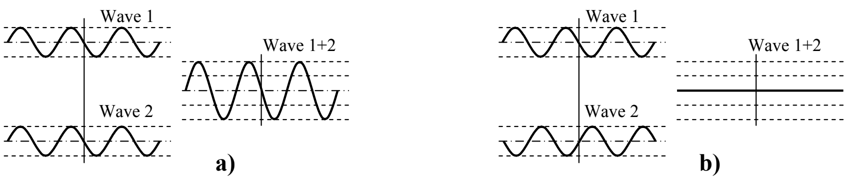

Figure 2. Constructive and destructive interference

Though modern day interferometers are more sophisticated, measuring distances to accuracies of the order of 1 ppm (parts per million) or better, they still use the basic underlying principles described above. The set-up for a linear distance measurement using the Renishaw ML10 laser system is shown in Figure 3. One retro-reflector is rigidly attached to a beam-splitter, to form a fixed length reference arm. The other retro-reflector moves relatively to the beam-splitter and forms the variable length measurement arm. The laser beam 1 emerging from the ML10 has a single frequency with a nominal wavelength of 0.633 μm and a long-term wave-length stability (in vacuum) better than 0.1 ppm, (all relevant

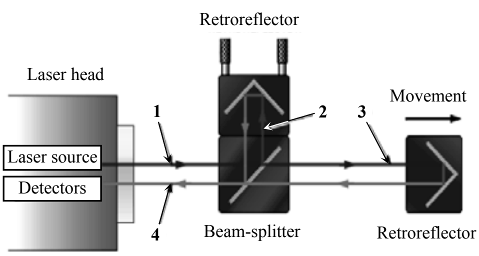

Figure 3. ML10 laser system

characteristics are shown in the Table 1). When this beam reaches the polarising beam-splitter it is split into two beams - a reflected beam 2 and a transmitted beam 3. The two beams travel to their retro reflectors and are then reflected back through the beam splitter to form an interference beam 4 at the detector, which is housed within the laser head. If the difference in path lengths does not change, the detector sees a steady signal somewhere between the two extremes of constructive and destructive interference. If the difference in path length does change, the detector sees a signal varying between the extremes of constructive and destructive interference each time the path changes. These variations (fringes) are counted and used to compute the change in the difference between the two path lengths. The length measured will be given by the number of fringes multiplied by the approximate half wavelength of the beam.

Table 1. Technical characteristics of ML10 laser

Laser source	HeNe laser tube (Class II)
Vacuum wavelength	632.990577 nm (nominal)
Laser frequency accuracy	ML10 Gold Standard: ±0.05 ppm
Outputs	5-pin data link
Power supply	ML10 Gold Standard has Universal Power Supply with auto-sensing input voltage range of 85 V to 265 V. Frequency tolerance: 45-65 Hz
Fuse rating	IEC 127 Class T (slow burn)
Operating temperature	0-40 °C
Operating humidity	0-95% non-condensing

It should be noted that the wavelength of the laser beam will depend on the refractive index of the air through which it is passing. Since the refractive index of air will vary with temperature, pressure and relative humidity, the wavelength value used to compute the measured values may need to be compensated for changes in these environmental parameters. In practice, for the measurement accuracies, such compensation is only required for linear displacement (positional accuracy) measurement where the change in the difference between the path lengths of the two beams is significant. The Renishaw ML10 system is a modular system, capable of measuring displacement, velocity, angular (pitch and yaw) displacement, flatness, straightness, parallelism and squareness, depending on the measurement kits supplied. A typical system set-up for measuring linear position is shown in Figure 4.

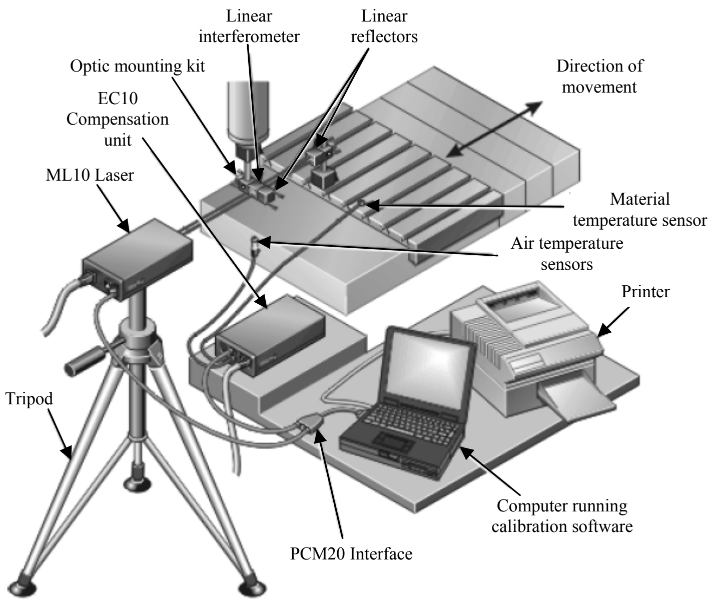

Figure 4. Typical system set-up for measuring a linear position

2. PRACTICAL EXAMPLES OF MEASUREMET

EXAMPLE No.1.

Machine Tools: CNC lathe, type Boehringer VDF DN 820. Axis of measurement: Z, type of measurement: linear displacement error measurement. Figure 5 shows the results of linear displacement error measurement. It may be noted that increasing the lengths from 400 mm to 800 mm error increases to a maximum of 140 μm.

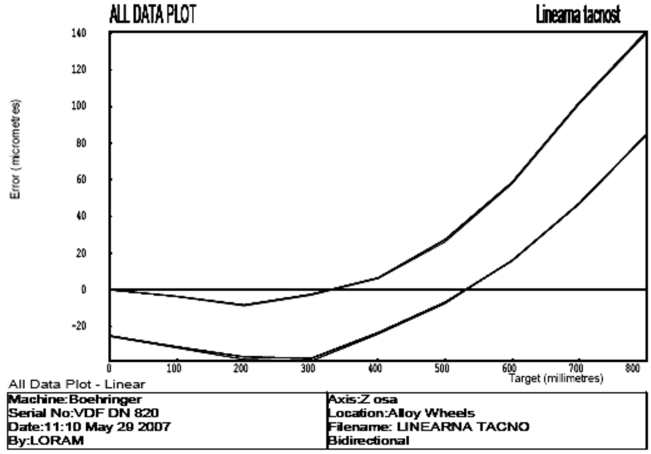

Figure 5. Results of linear displacement error measurement, CNC lathe, Z - axis

Machine Tools: CNC lathe, type Boehringer VDF DN 820. Axis of measurement: Z, type of measurement: angular (pitch) measurement, vertical plane. Figure 6 shows the results of this measurement. From mentioned figure it can be seen that the character of change of the measured error is same as on figure 5, but the value of the error in the length of 800 mm along the Z-axis is 0.16 μm, and it is possible to calculate angular error.

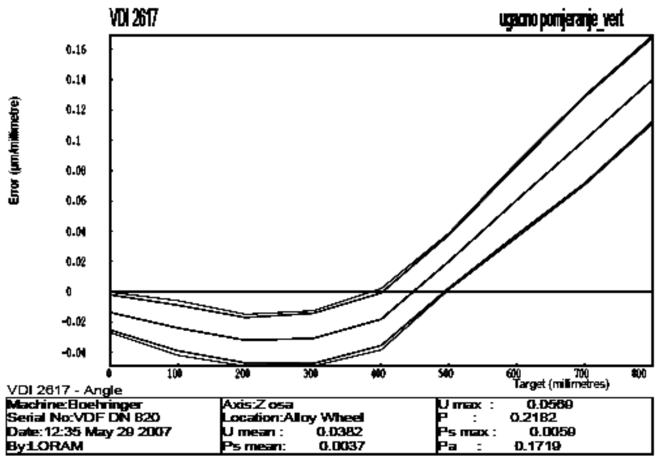

Figure 6. Results of angular (pitch) measurement, CNC lathe, Z – axis, vertical plane

EXAMPLE No.2.

Machine tools dynamic response is a very important feature of any machining process that strongly influences quality of a machined workpiece. It means that deterioration of a surface as a result of intense vibration in machine system can be prevented if source of vibration generation is firstly detected and after that removed from system. Beside the vibration generated in cutting process itself, vibration in machining can originated from many other sources too. Some of them are connected to machine tool elements like are: preload and hysteresis of ball screw and nut mechanisms; positional stability and encoder performance; resonance characterization of drive motors, spindles and other systems; stability and interpolation accuracy; control-loop optimization etc. To detect vibration source in practice different type of accelerometers have been utilized. Vibration signal collected from these devices is then processed by FFT (Fast Fourier's Transformation) in order to gain appropriate frequencies spectra and their amplitudes. The peaks or peaks frequency gives information about fault, and its intensity tells us about state of the source of vibrations. In this example, laser system is used instead of contact accelerometers to gain vibration response of a system.

Dynamic analysis of data using Ranishaw laser system enables following measurements: (i) distance, (ii) velocity, (iii) acceleration, (iv) amplitude and frequency of vibrations. These measurements allow monitoring and analysis of certain characteristics of a machine which can produce error, i.e.:

– pre-load and hysteresis of ball screw and nut mechanisms,
– positional stability and encoder performance,
– resonance characterization of drive motors, spindles and other systems,
– feedrate accuracy, stability and interpolation accuracy,
– control-loop optimization.

Using FFT (Fast Fourier's Transformation) on a signal it is possible to analyze vibration and determine its cause. The way of setting up laser and optics is shown in Figure 4.

Measurements were performed on CNC mill Deckel Maho DMU60 MonoBLOCK (Figure 7) during a movement of the main shaft along distance of ±80 mm in the direction of the Y axis. The velocity of the head movement – feed was 3500 mm/min. Setting up laser in this way it is possible to determine accuracy of machine's encoder and irregularities in feed mechanism of main shaft in Y direction. Three measurements are performed. First measurement is performed along distance of -55 do + 155 mm, second on distance of -72 do +88 mm and third on distance of -80 do +80 mm. Measurement results analyzed using FFT analysis are shown in figures 8, 9 and 10.

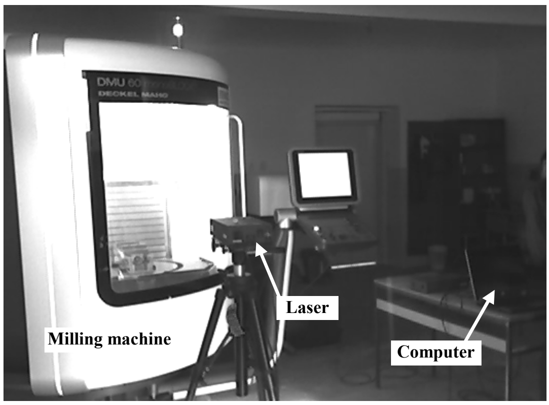

Figure 7. Experimental set-up for dynamic measurement

Total travelled distances of all three measurements were 160 mm. However starting position were not the same in all three cases. Beginning position in first and second measurement is not at the middle of interval, because the current position of the shaft was not taken under consideration. From the Table 2 it can be seen that three characteristic peaks exist with slight differences in all three measurements. Cause of these vibrations is necessary to investigate further.

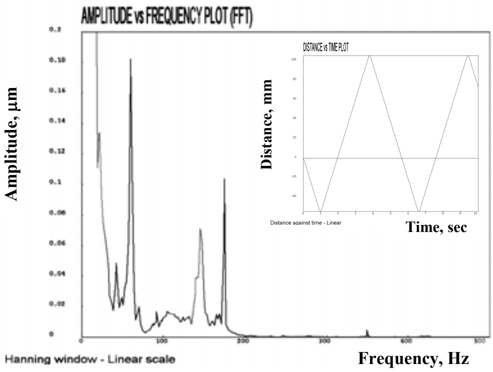

Figure 8. FFT analysis of the first measurement

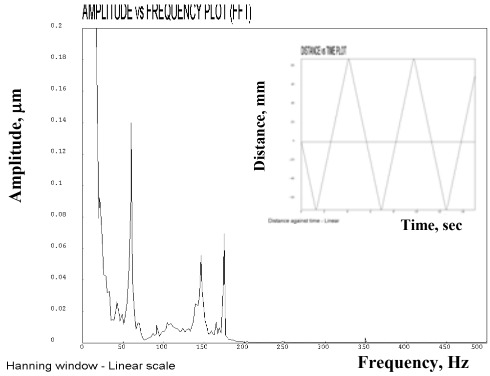

Figure 9. FFT analysis of the second measurement

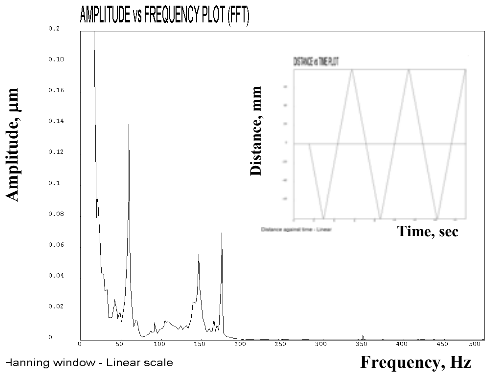

Figure 10. FFT analysis of the third measurement

Table 2. Frequency and amplitude of three most important peaks form figure 8, 9 and 10

Measurement	Peak frequency (Hz)	Amplitude (µm)	Measurement distance
1	59,89	0,18	-54,50 do + 105,50 (max measured -54,49048 +105,4703)
	144,95	0,07	
	174,40	0,05	
2	60,50	0,13	-71,75 do + 88,25 (max measured -71,73042+88,22912)
	146,30	0,09	
	174,80	0,12	
3	59,84	0,13	-80 do + 80 (max measured -79,9800+79,97965)
	146,02	0,05	
	174,70	0.06	

In the literature one can be found data about peak frequencies for most common machine failures. Peaks with frequencies of 1, 1½ and 2 x (rpm) indicate following faults: unbalance, eccentricity, misalignment, bent shaft, bad bearings and similar faults. In a given case three measurements of movement of the mill's main shaft in Y axis direction are performed. This movement is performed using ball-screw and nut mechanism. Diameter of the mechanism's shaft is 40 mm and feed is 20 mm. Considering the fact that shaft turns 8 times on 160 mm distance (4 times in one direction and 4 times in reverse direction), small number of revolutions of the mechanism's shaft cannot be related with frequencies of three main peaks shown in figures 8, 9 and 10. Influence of vibrations from nearby surrounding can be put out of the consideration since there are no sources of vibration in 500 µm radius. Source of these peaks are probably one or more bad balls of bal-screw and nut mechanism. Maximum and minimum distance registered by laser is different of that given to the machine. That means that in this way one can measure accuracy of the machines feed mechanism. In all three measurements accuracy was ±0.02 on a 160 mm distance what is in the acceptable tolerance range.

EXAMPLE No.3.

This example relates to the measurement axis deviations of main spindle and chuck device for deep drilling machine. Machine Type a LOCH (Germany) with a maximum drilling length of 4300 mm. Error deviation from straightness of the drilling of up to more than 5 mm

in length of 4000 mm is identified. Schematic interpretation of the machine is shown on Figure 11. Deep drilling machine is composed of two separate parts A (drive) and B (working table). These two parts are connected by screws and taper pins. On the other hand, both of these parts are separately supported and connected to the foundation screws.
In order to achieve concordance of main spindle and support the workpiece axis, it was necessary to rid the passage of the laser beam. For security, achieve straightness of beam, but also to facilitate manipulation, steering optics is placed in the front of the laser head.

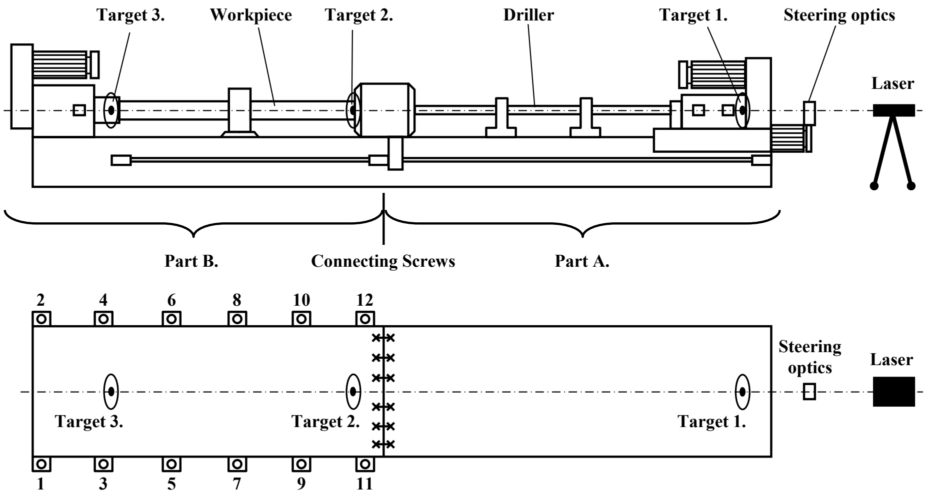

Figure 11. Shematic interpretation of deep drilling machine and measurement set-up

To rescue the perceived necessary to relieve foundation screws in Part B (12 screws, M12, six on the front and six on the back side, Figure 11). The sequence of measurements consisted of the following two steps: (1) By aligning the axis of the spindle and laser beam through three points: optics, target 1 and target 2 is achieved, (2) Target 3 is mounted on the left side of part B of machine tool. Thanks to the straightness of laser beam witch is passed through three targets, the ideal position between part A and part B of machine is obtained. After that, twelve foundation screws on the part B are tight.
Additional measurement of error deviation from straightness of the drilling of up to 0.5 mm in length of 4000 mm is identified.

EXAMPLE No.4.
Straightness measurement shows miss-alignment of an axis. This measurement identifies misalignment of a given axis from ideal one, or from reference guide way of a given machine element (Figure 12). This misalignment can come from wear of guide ways, damaged or poor machine foundations etc. This deviation of straightness has direct impact on a tool positioning accuracy. Renishaw ML10 laser system measures accuracy of straightness and repeatability of machine movement by measuring

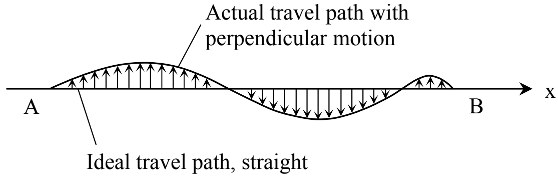

Figure 12. Definition of straightness

deviation of target points from reference axis. Using this system straightness of main shaft movement of CNC mill DM 60 monoBLOCK in direction of Y axis is performed. Measurement is performed on a length of 490 mm from outmost position towards machine bed. According to machine producers specification this deviation should be less then 0.02 mm on 300 mm length.

Laser source on this laser system is positioned on a tripod outside of a machine, while interferometer is positioned on a movable part and mirror is positioned on a stationary part of a given machine. Deviation of target points from reference axis, which is positioned between laser source and mirror on a stationary part of a machine, is measured. Typical system setup for straightness measurement using Renishaw laser system is shown in Figure 12. After optics are positioned and connected with laser management software the main shaft is moved from point to point 8 times on a 490 mm length. This procedure is repeated 3 times. The distance between target points is 70 mm. Measurement results are given on Figure 13. Maximum deviation on a given length is Umax=0.00436 which is considerably less from allowable 0.02 mm. This machine is calibrated upon its installation using dial gauge and length gauge. Length gauge is of 300 mm and overall deviation is 0.006 mm, what is in accordance to allowable deviation of 0.02 mm on a 300 mm length.

Figure 12. Real time setup for straightness measurement (left – optics, right – laser head)

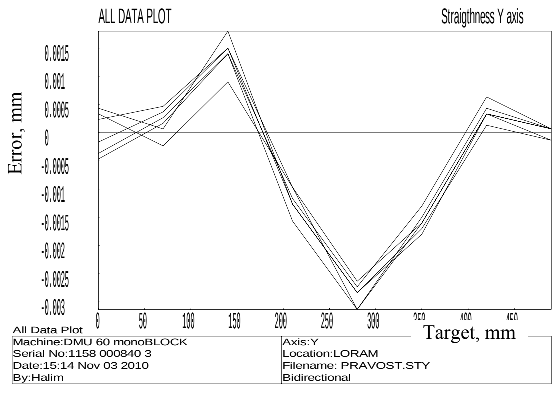

Figure 13. Graphical presentation of measurement results (Renishaw laser measurement system)

Way of optics setup for Damalini laser system is shown in Figure 14. Same movement as with Ranishaw laser system is checked. For straightness measurement this laser system uses to heads denoted with marks “M” and “S”. Head denoted with mark “M” is positioned on a main shaft which is performing movement in direction of Y axis. Head denoted with mark “S” is positioned on a machine bed, and it is stationary had which represent end point of reference axis. Disadvantage of this system is that reference axis is positioned between first and last point of the same movement which is under consideration. That is clearly visible from measurement results, according to which deviation in first and last point is 0. On contrary Renishaw laser system measures deviation in all target points. Measurement results, acquired using Damalini laser system, are shown in Figure 15 and Table 3. According to data given in Table 3, maximum straightness deviation is 0.004 mm.

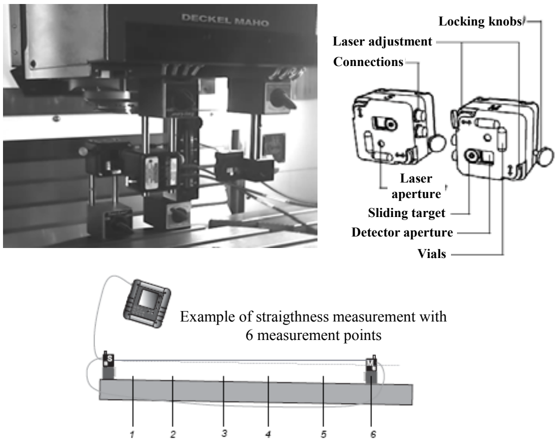

Figure 14. Damalini laser system set-up

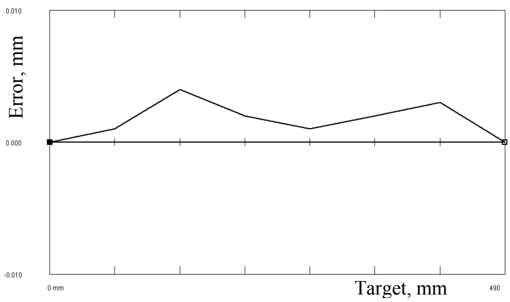

Figure 15. Graphical presentation of measurement results (Damalini laser measurement system)

Table 3. Measurement results (Damalini measurement system)

Point	Reference point	Distance, mm	Vertical deviation, mm
1	Ref.	0	0.000
2		70	0.001
3		140	0.004
4		210	0.002
5		280	0.001
6		350	0.002
7		420	0.003
8	Ref	490	0.000
Max		0	0.004
Min		0	0.000

So, straightness measurements procedure on a given machine tool, using two laser systems with different laser beam detection principle, is presented. Both laser systems showed that straightness deviation of Y axis on a given length is considerably less then allowable according to machine tool manufacturer specification which is 0.02 mm on a 300 mm length. Renishaw laser system gave more “precise” results with more decimal places comparing to Damalini laser which is limited to 3 decimal places (microns).

On the other hand setup procedure for Damalini laser system is much easier, take less time and still can give results in microns. This Damalini level of precision will meet calibration requirements for a number of machine tools systems. Yet for more precise calibration, in case of CMM for example, Renishaw systems offer significant advantage. When versatility of measurements are considered Renishaw system understandably gave more flexibility, since one have to keep in mind that this system is mainly aimed to machine tools calibration purposes. Additional difference between these two of laser systems is that for Damalini

sensors must be connected with cable. It means that measuring length is limited by length of cables, which is not the case when measures with Renishaw system.
According to above mentioned, one can conclude that both of the presented systems can gave significant help in regular machine shop maintenance activities. Yet the correct choice of measuring system have to take into consideration many other elements like purpose of a measured machine tool, requested accuracy and precision, place of a machine in production chain, available time, price of a machine and costs of maintenance.

3. CONCLUSIONS

The need for very precise measurements has emerged with evolution of automatic and CNC machine tools. Precision and accuracy are amongst main requests on modern machine tools. To define and know this characteristic of machine tools standard measuring procedures have been used for many years. Yet, others more advanced approaches and equipments, like laser measuring systems, are also available for measuring machine parameters like straightness of movements, repeatability, surfaces flatness, parallelism etc. This paper presents some examples of measurements of different deviations for different machine tools. These are measurement results of CNC lathe (deviation from linear motion), CNC milling machine (dynamic behaviour), deep drilling machine (straightness), CNC milling machine (comparative measurement straightness according to two different methods of measurement: interferometry and CCD method). Presented results can gave significant help in regular machine shop maintenance activities. Hence, the correct choice of measuring device and method in that sense can save time and decrease costs of machine maintenance.

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