XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

NEW METHOD FOR HIGH PRECISE ANGULAR MEASUREMENTS

V. Portman [1] ***and B. Peschansky*** [2]
[1] Department of Mechanical Engineering
Ben-Gurion University of the Negev, POB 653, Beer-Sheva 84105, Israel
[2] Placa Ltd., Prof. Bergman 2, Rabin Park, Rehovot 76705, Israel

Abstract: A new method of large-angle measurements is described. Its high accuracy results from averaging some thousands of readings of about hundred replicas of the measured angle. An optoelectronic device based on this method has been developed, produced, tested, and applied. The design and operation of the device is described. The device consists of optical grating scales of the regular accuracy. It results in simplification of the structure of the measuring device and increases its reliability. A calibration of the pilot batch of the device shows that its limit error is in the range of 0.5 arcsec. Examples of the real-life applications of the device for different setups of the measured equipment provide support for high accuracy and high efficiency of the developed method.
Keywords: Accuracy, Angular measurement, Optoelectronic device

1 INTRODUCTION

The subject of this paper is the method and instrumentation for high precision large-angle measurements under operating conditions. Accuracy of angular displacements of rotary machine axes is one of the topical problems for machine tools, robots, rotary indexing tables, and so on [1-4]. High precision measurements - i.e., the measurements with an accuracy in the region of one angular second and better - are usually performed by systems consisting of optical polygons, autocollimators, and laser interferometers. Currently, the topical direction of the development of the precise angular measurements is application of optoelectronic devices - optical encoders [2]. A cumulative error of the applied grating scales, as a rule, is the major portion of the error of these devices. Known means for increasing their accuracy make the encoder structure more complicated, decrease its reliability, reduce the signal-to-noise ratio, etc.

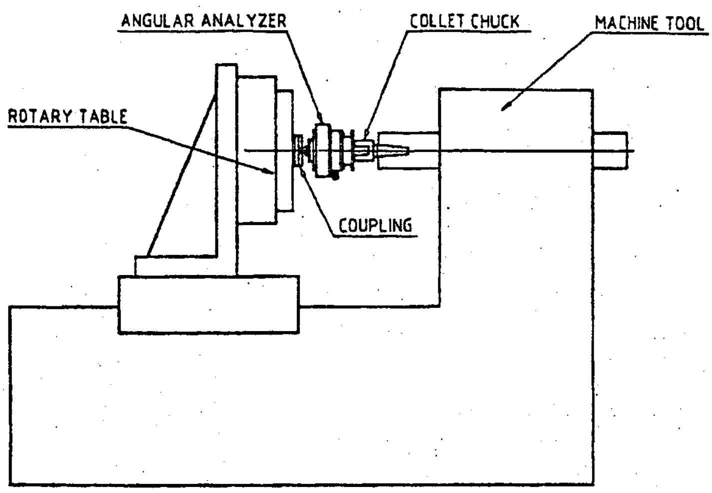
In this paper, a new type of optoelectronic device is described [5]. The high accuracy of the device is based on an approach where several thousands of measurements are performed for each of the phase angles, and then the results of these measurements are averaged. This approach enables us to apply optical grating scales of regular accuracy in the developed precision device. In turn, it results in simplification of the structure and increases the reliability of the device. The device is meant for measurements in conditions of precision manufacturing, and meets requirements for high precision and high performance.

The pilot batch of these devices has been produced by Placa, Ltd. Commercial grating scales of regular accuracy with 3600 divisions were used; a cumulative error of these scales is of about 12-15 arcsec. Thanks to statistical averaging of this error, the accuracy of the device is increased by a factor of tens to hundreds. A calibration shows the accuracy of the device is in the range of $\pm$0.2 arcsec. The effectiveness may be displayed as follows: a complete cycle of measurements of a rotary table (an angle range is 0 - 360 degrees, and the angle increment is one degree), is carried out in about 20 - 30 min., including setup time.

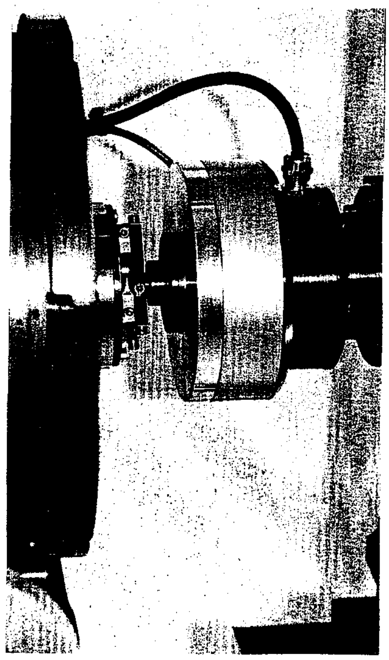
2 DESCRIPTION OF THE DEVICE

The device consists of a transducer and an electronic data processing unit. The analyzer mounted for measuring the accuracy of the precision rotary table on the machining center is shown in Fig. 1. The collet chuck and precision coupling link the device with the machine tool spindle and the measured table axis, respectively. The angular analyzer consists of two parts: a transducer and an electronic data processing unit. The diverse adapter versions enable one to install the transducer when the axes of the spindle and the table are collinear in vertical or horizontal positions, as well as when they are perpendicular to each other. Other optional connections are also possible.

The axial section of the transducer is shown in Fig. 2. Shaft 12 with measuring disk 11 is rigidly bound to the rotating axis of measured table 13. This unit can rotate at a rate up to 20 rpm with respect to casing 4. The casing is rigidly fixed relative to the machine base. For the setup in Fig. 2, the casing is connected with mandrel 1, which, in turn, fixed in the immobile spindle of the machine tool. To provide the possibility of different relative positions of table 13 and mandrel 1, connections have flexible coupling 14 and ball-and-socket joint 2, respectively.



(a)



(b)

Figure 1. Setup for measurements of the CNC rotary table (a) and a general view of the device (b)

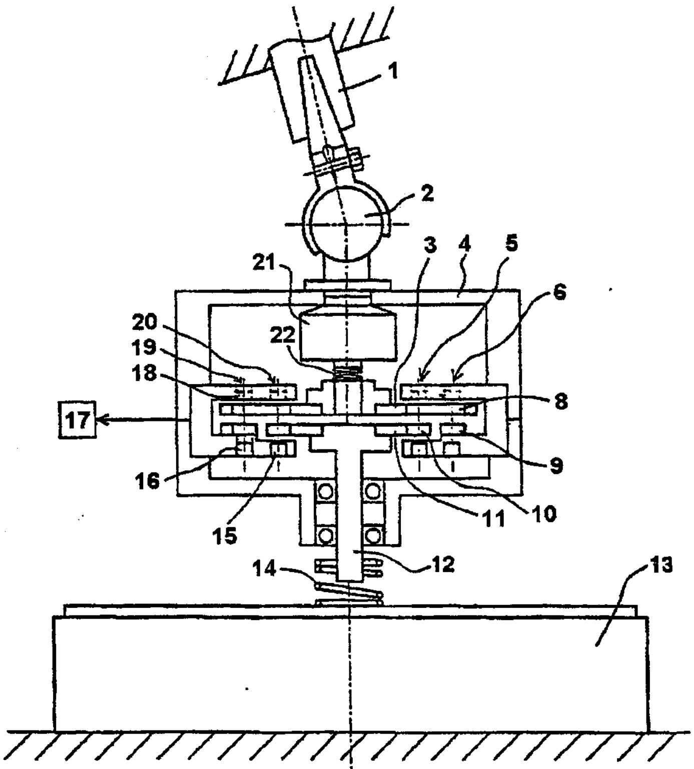


Figure 2. Schematic diagram of the cross section of the measuring device.

In the transducer, there are three concentric optical grating scales: scanning scale (ScS) *8*; basic scale (BS) *9*; and measuring scale (MS) 10. The grating scales made up of alternating lines of high and low transparency, typically with a sinusoidal variation of transmissivity. ScS 8 is located on scanning disk 3; MS 10 is located on measuring disk 11; and BS 9 is fixed relative to casing 4 and hence to the machine metrological frame. Kinematics of the three disks with optical scales is as follows. ScS 8 continuously rotates at a steady rate and is driven by motor 21 through flexible coupling 22. BS 9 has no motion with respect to the reference frame (in this case, casing 4); and MS 10 can rotate or be stopped with respect to the reference frame, depending on a performed stage of the measuring process. All the grating scales have the same number N of radial opaque lines (e.g., N = 3600). The scale of ScS 8 on scanning disk 3 has relatively large dividing lines, which cover in length both MS 10 of measuring disk 11 and BS 9.

Photoelectric sensors 19 and 20 generate electric current signals, which are then processed by processor 17 to calculate information relating to the precise angular position of shaft 12 relative to base 1. The signal of sensor 19 corresponds to variations of optical transmissivity through a combination of scales 8 and 9, and the signal of sensor 20 corresponds to these variations through a combination of grating scales 8 and 10. The device has four pairs of these sensors, which are located in 90 degree intervals around the periphery of the divided disks. One more pair (sensors 5 and 6) is shown in Fig. 2. These sensors are diametrically opposite to sensors 19 and 20. Two other pairs are located on the perpendicular diameter.

3 DEVICE FUNCTIONING

The transducer functions as follows. The sensors generate oscillating electric current signals, which are then processed by the processor. A light beam produced in the external sensor in pair intersects the lines of the ScS and BS. As a result, a “reference signal” is generated (Fig. 3). Similarly, another light beam within the internal sensor in the pair intersects the lines of the ScS and MS; this results in generating the "measured signal."

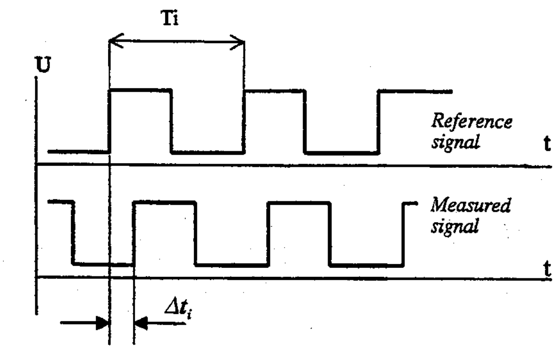


Figure 3. Relative position of the base and measuring signals.

Using these signals, one can calculate the measured angle θ as follows:

$$\theta = \alpha n + \varphi \qquad (1)$$

where α is angular value of the scale graduation, $\alpha = 360^o/N$; n is the integer number of scale division in the measured angle (0 n N - 1), which is measured when the measuring disk rotates; the number n is counted during rotation of scanning scale with respect to measuring scale; φ is the phase angle, which is calculated as an average of N K measurements,

$$\varphi = \sum_{i=1}^{N}\sum_{k=1}^{K} j_{ik} /(K N); \qquad (2)$$

where K is the number of copies of the phase values come into the view of the photosensors, which are form K replicas φ_{i1}, φ_{i2},..., φ_{iK} of the phase angle; N measurements are obtained during one complete revolution of the ScS when the BS and MS are stopped; φ_{ik} is the phase replica,

$$\varphi_{ik} = \alpha \Delta t_{ik} /T_i; \qquad (3)$$

Δt_{ik} is the time interval corresponding to the phase angle, i.e., the time between the first adjacent pulses of the reference signal and the measuring signal pulse which follows it; the current time in the process of measurements is given by a control clock (e.g., with clock rate 40 MHz); the portion of time T_i (ith period of cycle, where i is the current number of the dividing line of the ScS, with i = 1,...,N) is measured between two consecutive maxima (or two zeros) of the reference signal; the nominal value T_i is $T_0 = 2\pi/(N\,\omega)$, where ω is the angular frequency, rad/s, of the ScS rotation.

Thus, the angle θ is measured in two steps. In the coarse step, the number n is counted during rotation of scanning scale 8 with respect to measuring scale 10. The second (fine) step are performed after stopping disk 11 with the measuring scale 10. In this step, phase φ is measured NK times and calculated by formula (3). A fragment of the results of the phase measurements is shown in Fig. 4, where two curves present photosensor-obtained readings. The curves show the signals of two sensors and have 600 readings each. The readings are obtained when the scanning scale was turned through 60^o and given in the time pixels (1 pixel = 0.14 arcsec).

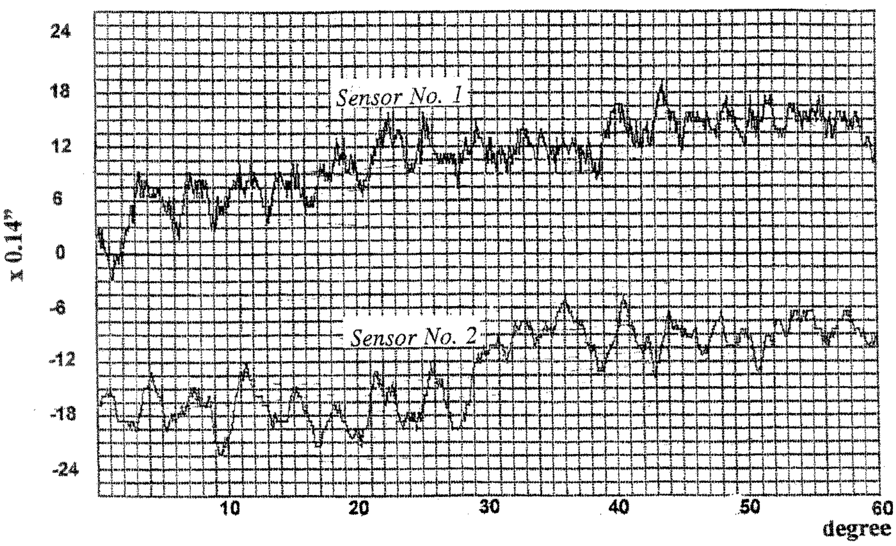


Figure 4. A fragment of the current phase measurements.

Data processing is performed by an electronic unit (Fig. 5). It consists of a signal processor, a mode switch, a zero-crossing counter, a timer, a memory, and a microprocessor. Peripheral devices of the processor are a display, a port, and a control panel. The signal processor receives a pair of reference and measuring signals and converts them into the square-wave pulses. The switch sets the mode of the processor, depending on whether shaft 12 (Fig. 2) rotates or not. When the shaft rotates the switch switches to pass the signals to the phase shift zero-crossing counter for coarse measurement of angular position, i.e., the number n in Eqn. (1). This counter maintains a cumulative count of zero-crossing of the phase shift between the reference and measuring signals. The number n is passed to the microprocessor. Alternatively, when the shaft 12 is stationary, the mode the switch switches to pass the signal to the timer for precise stage measurements, i.e., for measurements of phase φ.

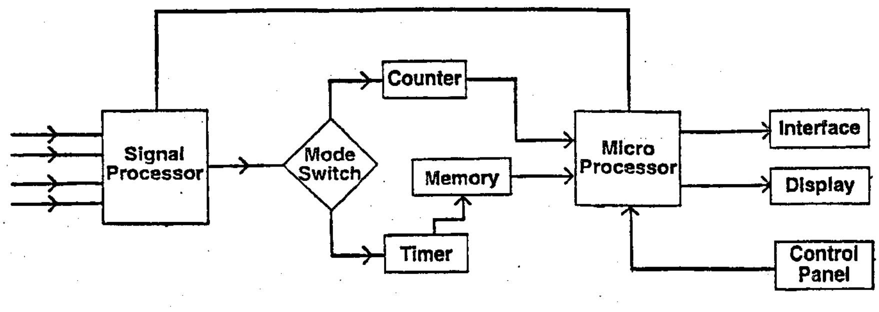


Figure 5. Flow chart of the electronic data processing.

The timer derives a set of data pairs (T_i, Δt_i) entering into Eqn. (3). This data is then accumulated in the memory, and calculations according to Eqns. (2) and (1) are carried out by the microprocessor.

4 ACCURACY ASSESSMENT

The accuracy of the output signal (1) is completely defined by an error of the measurement of the phase angle φ, Eqn. (2). It is very important that statistical characteristics of the sequence of time data $\tau_T = (T_i, T_{i+1},...,T_{i+N-1})$ is independent of the start number i = 1,...,N. This stems from the fact that N counts include all the scale errors because of complete revolution of the scanning disk. Therefore, the standard deviation σ_φ of the angle φ, Eqn. (1), may be presented as follows [6]:

$$\sigma_\varphi^2 = \frac{1}{KN}\left[\left(\frac{\partial\varphi}{\partial\Delta t}\right)^2_{T=T_0}\sigma_1^2 + \left(\frac{\partial\varphi}{\partial T}\right)^2_{T=T_0}\sigma_2^2\right] = \frac{1}{KN}\left[\sigma_1^2 + \left(\frac{\Delta t}{T_0}\right)^2\sigma_2^2\right] \quad (4)$$

where σ_1 and σ_1 are the standard deviations of the random variables Δt_{ik} and T_i, respectively.

Taking Δt_{ik} and T_i to be the normal distributed random values, one can substitute limit deviations Δ_1 and Δ_2 of these random values for their standard deviations σ_1 and σ_2. To estimate the device accuracy, consider the potential components of the total errors. According to the method of measurements, the time interval Δt_{ik} is measured by means of three scales and the time period T_i is measured by means of two scales. Since the relative position of the scales are independent of each other, the limit deviations Δ_1 and Δ_2 of the random values Δt_{ik} and T_i may be estimated as $(\Delta_1)^2 = 3\,\delta^2$ and $(\Delta_2)^2 = 2\,\delta^2$. Therefore, the calculation by formula (4), with the above-mentioned substitution of limit deviations for standard deviations, yields:

$$\Delta^2 = [3 + 2\,(\Delta t/T_0)^2]\,\delta^2/(K\,N) \quad (5)$$

where Δ is the limit deviation of the phase angle φ. Since 0 Δt T_0, the maximum value of the limit deviation is established when the measured phase is maximal, i.e., $\Delta t = T_0$. In this case, we obtain:

$$\Delta^2 = 5\,\delta^2/\,(K\,N)$$

For example, if N = 3600, δ = 20 arcsec, and four sensors each have 20 scale spaces in view, we obtain K = 80 and $K\,N$ = 288,000. Thus, calculation by formula (5) of the theoretical accuracy of the developed device yields: $\Delta = [5/(K\,N)]^{-1/2}\,\delta = 20\,/\,(57600)^{-1/2}$ = 0.0833 arcsec.

The corresponding calculation of the accuracy, when small phases ($\Delta t \ll T_0$) are measured, yields $\Delta = [3/(K\,N)]^{-1/2}\,\delta = 20\,/\,(96000)^{-1/2}$ = 0.0645 arcsec.

5 REAL-LIFE APPLICATION

A pilot batch of the devices was produced, tested, and applied in real-life conditions. For these devices, N = 3600, δ = 20-25 arcsec, and four sensors each have 20 scale spaces in view. Thus, formula (5) of the theoretical error yields Δ = 0.104 arcsec. The device was calibrated by the PTB (Physikalisch-Technische Bundesanstahlt, Germany). The angle comparator [7] with reproducibility within ±0.01 arcsec was used for the calibration procedure. The results are as follows: mean error is better than ±0.2 arcsec, the standard deviation is better than 0.05 - 0.15 arcsec.

As an example, CNC rotary indexing table was tested by this device. The measurements were performed at 10 degree intervals in the automatic mode (Fig. 6). The measurements range was from 0 to 350 degrees in clockwise and counter-clockwise directions. Ten-fold repetition (700 readings) of the total cycle of the measurements took less than one hour. The first run of measurements was used to carry out the correction procedure for error compensation of the measured rotary table. Thereafter the total cycle of the measurements was repeated. A comparison demonstrates that cumulative error was reduced by the factor 16.4, i.e., from 37.7 to 2.3 arcsec (see curves 1 and 2 in Figure 6).

6 CONCLUSION

The new method of large-angle measurements has been developed. According to the method, about hundred replicas of the angle is simultaneously measured; then this set of measurements is repeated some thousands times, whereupon all the results are averaged. This principle of total averaging in common with phase angle measurements enables one to achieve the high accuracy using the regular incremental optical scales, without recourse to effects of diffraction and

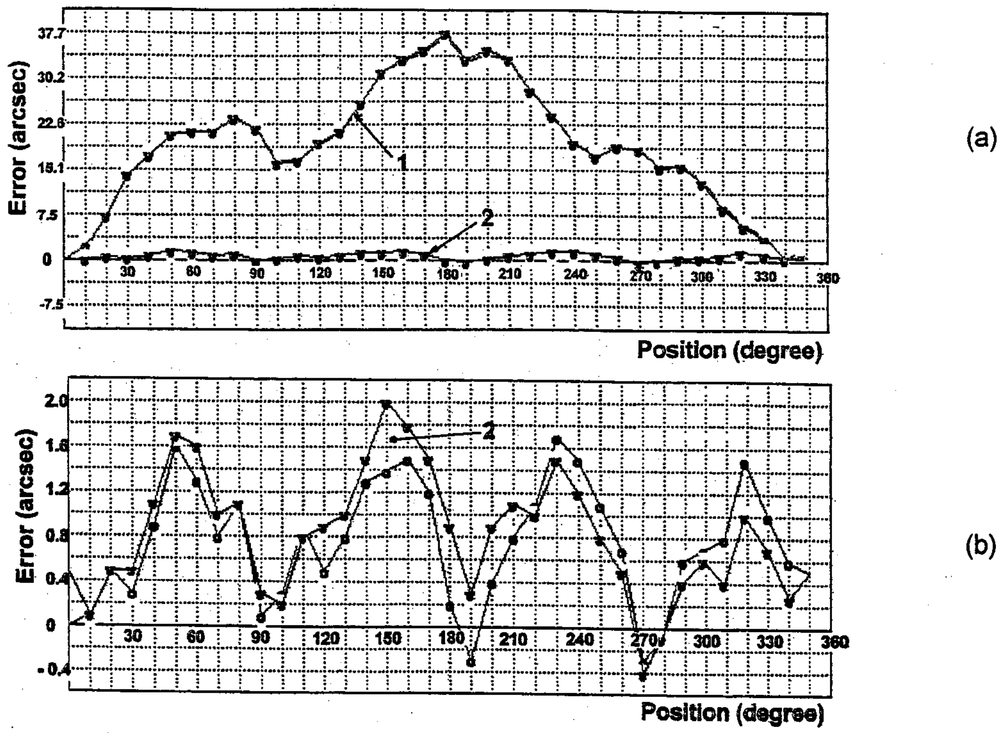


Figure 6. (a) Results of measurements of the rotary table accuracy: 1 - before error compensation; 2 - after error compensation. (b) The detailed results of measurements after error compensation.

interference of light. It results in simplification of the structure of the measuring device, increases its reliability and productivity. The optoelectronic device based on this method is developed, produced, and tested. Examination of the experimental batch of the device shows the accuracy better than 0.5 arcsec for one complete revolution of the measured axis.

7 ACKNOWLEDGEMENT

One of the authors is grateful to the Paul Ivanier Robotics Research and Production Management Center for its encouragement.

REFERENCE

[1] Hocken, R., *Machine Tool Accuracy*, University of California, Livermore, CA, 1980.
[2] Slocum, A., *Precision Machine Design*, Prentice Hall, Englewood Cliffs, NJ, 1992, 750 pp.
[3] Moore, W.R., *Foundation of Mechanical Accuracy*, The Moore Special Tool Co., 1970, Bridgeport, CO, 354 pp.
[4] Reshetov, D., and Portman, V., *Accuracy of Machine Tools*, ASME Press, NY, 1988, 304 pp.
[5] Peschansky, B., et al., *USA Patent No. 5,698,851*, Priority of Dec. 16, 1997.
[6] Hudson, D.G., *Statistics: Lectures on Elementary Statistics and Probability*, 1964, Geneva.
[7] Probst, R., et al., *The New PTB Angle Comparator*, Meas. Sci. Technol., 9, 1998, 1059-1066.

AUTHORS: Prof. V. PORTMAN, Department of Mechanical Engineering, Ben-Gurion University of the Negev, POB 653, Beer-Sheva 84105, Israel, Phone Int ++972-7-6477093, Fax Int ++972-7-6472813, E-mail: portman@menix.bgu.ac.il
Dr. B. PESCHANSKY, Placa Ltd., Prof. Bergman 2, Rabin Park, Rehovot 76705, Israel, Phone Int ++972-8-9462765, Fax Int ++972-8-9462665,