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SPINDLE ERROR MOVEMENTS MEASUREMENT ALGORITHM AND A NEW METHOD OF RESULTS ANALYSIS

Machining accuracy depends not only on geometric precision, but also on machine tool spindle error motions. This is particularly important for machining with high rotational speed. Spindle error movements are precisely defined and the method of their measurement methodology is standardized (ISO 230-7 and B89.3.4). Also devices for measuring the error movements are generally known. The main problem is the development of algorithms to ensure the proper measurement, interpretation accordingly to the standards, especially considering so called sensitive and non-sensitive directions. This paper presents an approach and algorithms of spindle errors movements measurement. The proposed methodology is more reliable than commercial solutions.

1. INTRODUCTION

Only ideal (non-real) spindle has one, the theoretical axis – the axial line in the drawing. In reality, the spindle consists of a series of interacting surfaces which are made with a certain (finite) accuracy. Every surface has its own axis, so all axes are overlapping, mutually nonparallel. Objectively existing is the spindle rotation axis determined by the surfaces of bearings. Unfortunately, this rotation axis is not stationary. Unwanted movements, made by this axis, dependant on the spindle condition, have an influence on the surface quality, tool life, the dimensional accuracy of the workpiece. The methods of machine tool geometric accuracy measurement are well known. The measurements are carried out statically or with very low rotational speed, for example eccentricity test (runout) which discloses the performance or assembly errors, indicating misalignment of the bearing surfaces with the measured surface. The runout however, is not movement error – a spindle with runout can rotate around a stationary axis. In case of the machine tool spindle it is important to measure the change of the axis rotation position during rotation at high speeds. The measurements of spindle error motions are recommended by international standards [1] and the US [2],[3]. The standards define the basic concepts related to the error motions,

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provide a number of recommendations, but do not provide a detailed methodology of data acquisition and interpretation.

2. ERROR MOTION POLAR PLOTS

Every rotating spindle has one large degree of freedom: Θ_Z – rotation around fixed reference axis Z_R, and five small error motions (Fig. 1):
- rotation around axes X and Y perpendicular to spindle axis: ε_X and ε_Y,
- movement along three reference axes X_R, Y_R and Z_R: δ_X, δ_Y and δ_Z.
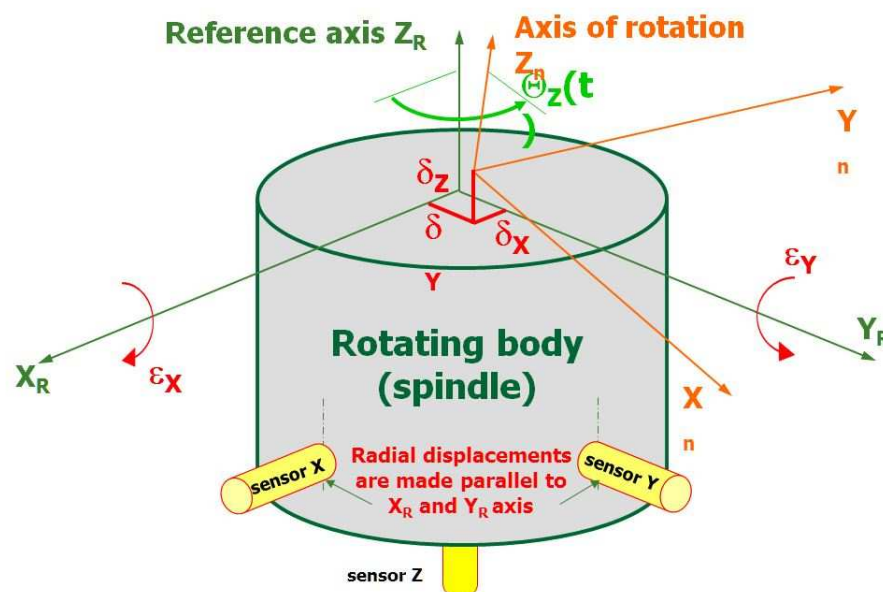

Fig. 1. Rotary motion axis errors

These error motions can be measured using a non-contact sensor mounted close to the target of regular shape fixed on the spindle. Measurements made during high-speed rotation of the spindle (several dozen or more measurements during one rotation) indicate error motions in the stationary reference system. Measurements in the directions X_R and Y_R should refer to the same point on the surface of the rotating target, which is extremely important. For precise determination of the angular position of the spindle, used algorithm requires a studious measurement procedure and, above all, accurate determination of the rotational speed of the spindle. Displacements in the sensitive directions, perpendicular to the machined surface, are important from the machining accuracy viewpoint. This direction is fixed for turning process (as a tool - Fig. 2a). As the error motions measurements are made in a plane perpendicular to the axis of the target, it can be limited to a single sensor. In the milling process the sensitive direction rotates with the tool (Fig. 2b), thus movements along this direction must be measured by two fixed sensors in X_R and Y_R axes. The result of a single measurement is shown in Fig. 3.
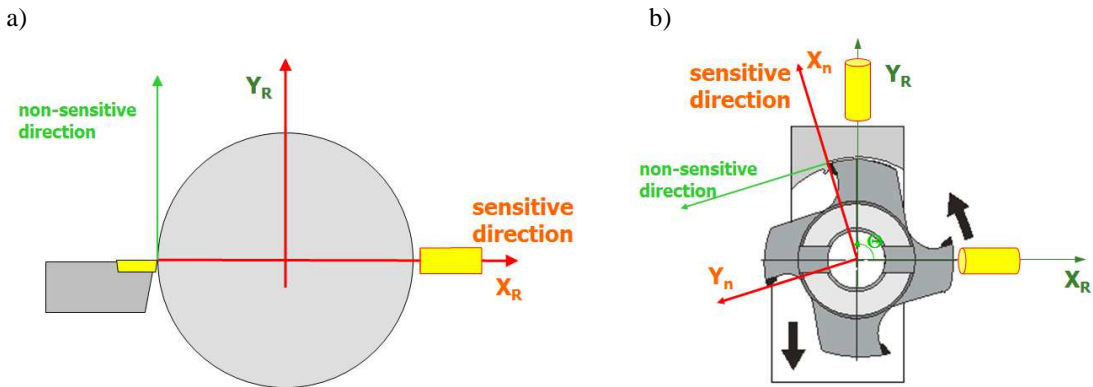
Fig. 2. Sensitive directions at: a) stationary in turning b) rotating in face milling
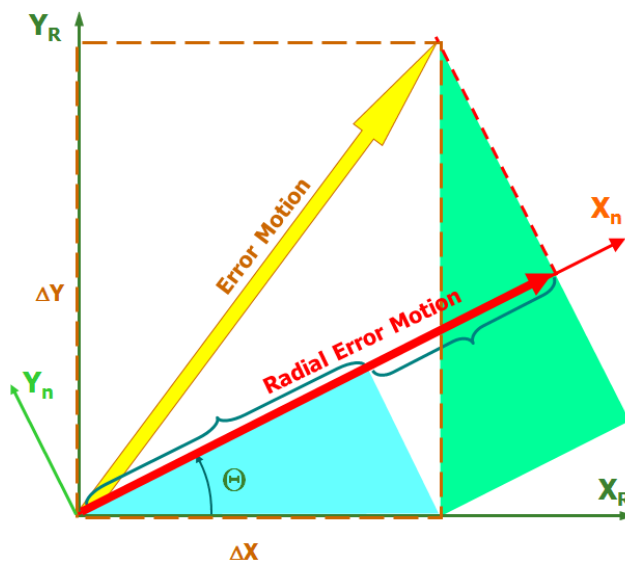

Fig. 3. Calculation of Radial Error Motion

The error motion (marked by yellow arrow - Fig. 3) has to be projected for sensitive direction X_n as a function of the angle of rotation according to the formula (1):

$$REM(\theta) = \Delta X(\theta)\cos(\theta) + \Delta Y(\theta)\sin(\theta) \qquad (1)$$

As both ΔX and ΔY displacements can be positive and negative the obtained plot would be tangled, unreadable. Therefore, a Radial Error Motion Polar Plot is used as a conventional and useful form for displaying data of radial error motion measurements. The way of obtaining a single point of this plot is presented in Fig. 4. The spindle axis deviation from the nominal (average) position, measured by two sensors, is marked as point 1. Point 1' is obtained by adding the eccentricity of the target r_0. As already mentioned, the eccentricity of the target is not an error motion, hence the circle drawn by the radius r_0 is the reference circle, representing an flawless rotation of the spindle. Then, point 1' should be projected on sensitive direction determined by the current angle of the spindle rotation θ – point 1" on radial error motion a polar plot:

$$r(\theta) = r_o + \Delta X(\theta)\cos(\theta) + \Delta Y(\theta)\sin(\theta) \qquad (2)$$
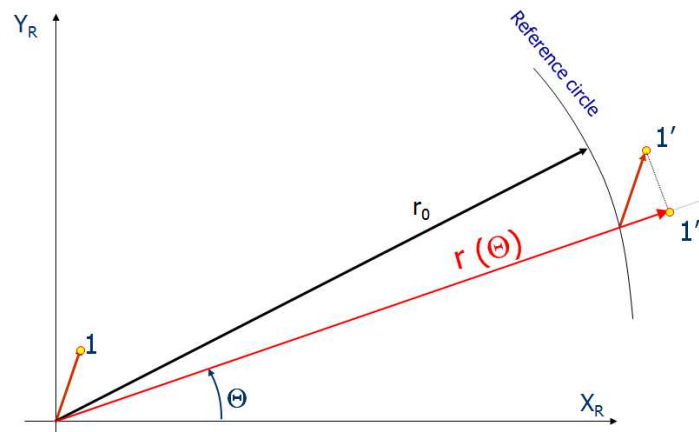

Fig. 4. Creation of error motion polar plot

Test data from rotating measurements are displayed with a polar plot showing the target position at successive angular locations on successive rotations, projected on sensitive direction (radii) and are evaluated, in a manner similar to the roundness plot of a machined part.
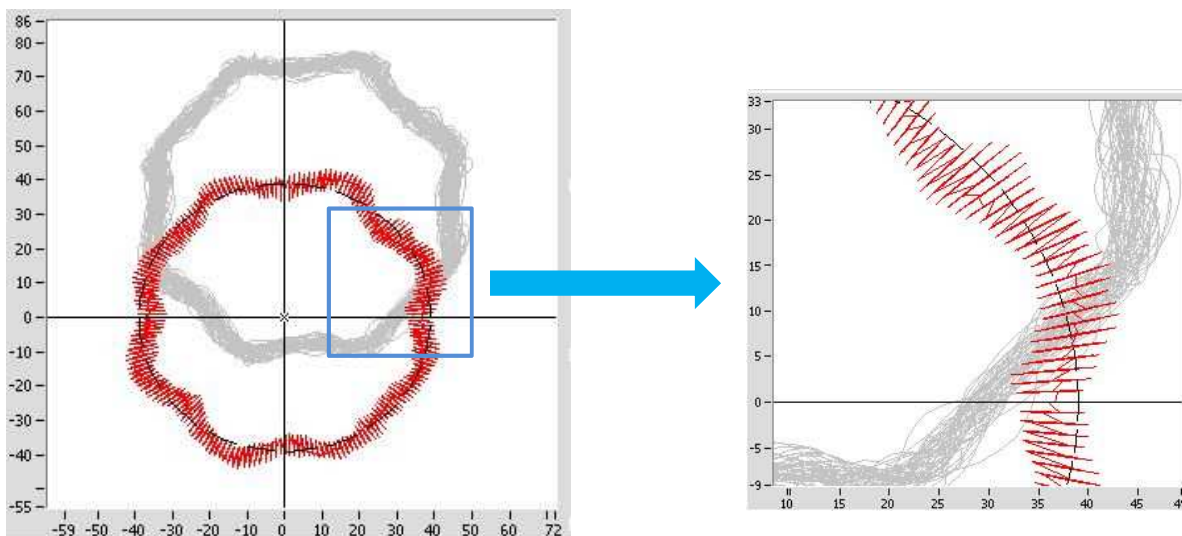

Fig. 5. Error motion polar plot

The gray line in the background, in the X_R-Y_R plot (Fig. 5) shows direct measurement results from X and Y sensors, and the red line shows measurement results projected on sensitive directions corresponding to the individual angular positions of the spindle. Determination of the radial error motion is based on circle radii defining the ideal and the real movement of the rotating spindle. At the beginning, the reference circle representing a fixed axis of the spindle rotation is calculated using least squares method (LSC - Least

Squares Circle). The LSC center, together with the plot, moves to the center of the coordinate system. Its radius is a result of the eccentricity of the target with respect to the axis of rotation, and has no relation to the error motions. This eccentricity can be deliberately entered to allow the determination of the spindle speed and angle of its rotation θ. LSC radius can also be arbitrarily changed or even created virtually (mathematically) in order to make the plot more readable.

Thus the error motions polar plot shows the radial deviation of the spindle axis position form the central (average) position collected during several spindle revolutions, arranged with respect to the spindle axis rotation angle θ position, marked with radial red lines in Fig. 5. This plot is base of further analysis – determination of the total, synchronous (correlated with rotation) and asynchronous errors.

3. ERROR MOTIONS AND THEIR INTERPRETATION

According to the standards the total error motion is a "complete error motion as recorded, composed of the synchronous and asynchronous components of the spindle" [1]. Its value is the worst possible case, initially specifying accuracy of machine tools. Therefore, evaluation of the total error motion is based on two circles concentric with the reference circle. The first circle is drawn in the blank area inside the plotted data with the largest possible radius without encroaching on the data (maximum inscribed circle – red in Fig. 6). The second circle is drawn in the blank area outside the plotted data with the smallest possible radius without encroaching on the data (minimum circumscribed circle – red in Fig. 6). The difference between the radii of these two circles is defined as the **total error motion value**.
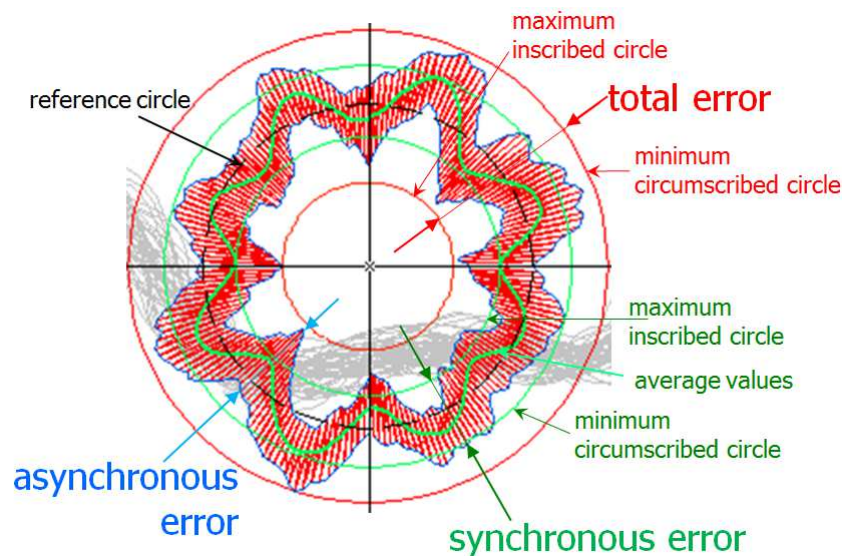

Fig. 6. Evaluation of Radial Error Motion

Asynchronous Error Motions are not related to the rotational frequency of the spindle. While their source may be well defined and repetitive, they are not synchronized to the spindle rotation, e.g. they repeat at a frequency that is not a multiple of the rotational frequency. The Fig. 6 shows a radial error motion plot for fifty revolutions. The "fuzziness" of the plot indicates that at any particular angular location, the location of the target varied significantly on each successive revolution. Once the data has been taken, the range of data (maximum - minimum) is determined at each angular location. The largest range (worst case) is defined as the asynchronous error value.

Error motions that are related to the rotational frequency of the spindle are called **synchronous or average error motions**. If the error motion were completely synchronous, the plot of data would draw a pattern with the same value at each angular location on each successive rotation. Because there is always some amount of asynchronous error present, the synchronous error must be extracted from the asynchronous data. First the values at each angular location are averaged. Like total error, maximum inscribed circle and minimum circumscribed circle that just contain the averaged data are drawn (green in Fig. 6). The synchronous error motion value is defined as the difference in radii of these two circles.

The rotation angle of the spindle – θ in equation (1), is fundamental for determining of the errors described above. Its determination, as well as the entire data acquisition methods are not obvious, especially when we are talking about rotary speeds from 100 to 1000 rev/s. The standards did not specify the methodology of spindle angular position determination, leaving this to the researcher initiative. Commercial systems for spindle error analysis, not necessarily meet the requirements of the standard, by analyzing for example, erroneous movements without the projection them of the sensitive direction [4]. Hence, presenting the issue of these measurements in more detail might be worth attention.

4. ERROR MOTION ACQUISITION

While testing the commercial programming of the spindles motion error analysis problems occurs when the spindle rotational speed is unstable. It is possible to determine the rotational speed using additional sensor as well as a marker on the spindle and this option in commercial layouts is provided. Nevertheless, this solution is inconvenient for rapid testing machine tools in a manufacturing workshop. Also with high-speed spindles adding a rotation marker (additional mass) to the rotating element is problematic.

In the algorithm presented in [5], the first stage of the procedure is the precise determination of the spindle rotational speed. For this purpose an eccentric target was used intentionally as in commercial layout, but the rotational speed calculation algorithm is different. According to the proposed algorithm the 100 000 samples must be taken with the sampling rate f_s=100kS/s from sensor X. The dominant frequency component, is the spindle rotational speed in revolutions per second (rps). Fig. 7 shows the first 2000 samples done during this kind of measurement.

As can be seen here, the signal is strongly disturbed (and this is not the worst case), so precise evaluation of main frequency component is not easy. One of the library LabVIEW
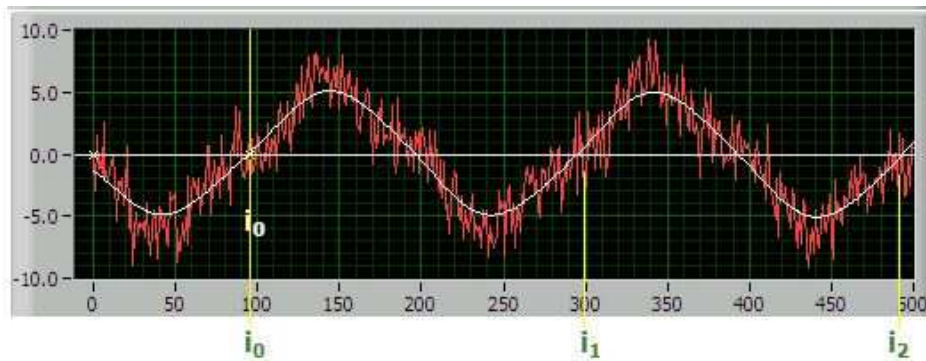
Fig. 7. The signal obtained during spindle speed measurement and evaluation of radial error motions

functions (e.g. „Extract Single Tone Information") can be used, but better results, gives an application of the procedure described below:
-   the signal X is a heavily low-pass filtered, ensuring avoidance of introducing any phase shift,
-   exact (not integer) values of the beginning of each spindle revolution i_j are determined,
-   obtained sequence of i_j values can be described by:

$$i_j = i_0 + j \, n_R \tag{3}$$

where: j – rotation number, i_j – number of sample beginning the j-th rotation, n_R – number of measurements per spindle revolution
   – the value of n_R and i_0 can be evaluated using last square method from [i_j, j] array as slope and the intersection point of the line (3)

The spindle speed is calculated as:

$$rps = f_s/n_R \tag{4}$$

This method can also be used when the rotation marker is not approximately sinusoidal signal from the eccentricity, but for example an additional sensor which checks one or more holes in the rotating target when the library LabVIEW functions cannot be used. Determination of the exact rotational speed allows for precise selection of the sampling frequency to achieve an appropriate number of point measurements per rotation. It has been assumed, that error movement measurements should be performed in 200 angular positions of the spindle (every 1.8°) during 50 revolutions, which means, that 10000 samples should be acquired with sampling frequency f_s=200*rps. The actual error movement measurements are carried out immediately after the spindle speed determination. Then just after this measurement, the spindle rotation speed determination is performed once again. If the difference between the two measurements is bigger than 1%, all the measurements and calculations are canceled and repeated again. This procedure eliminates measurements during the spindle speed changes. The whole cycle takes approximately 3 seconds and is called and executed automatically.

Projection of the deviations of the spindle position on the sensitive direction (1), necessitates exact identification of the angular spindle position of each measurement. This can be achieved as follows:

- the entire original (not filtered) signals X and Y are divided into separate revolutions (n_R points each) using beginning of each revolution i_j accordingly to eq. (3); as the n_R is the real number, the revolutions can overlap,
- measurements in each rotation correspond to subsequent angular positions of the spindle θ, with step $2\pi/n_R$, and accuracy to $1/n_R$ radian.

5. EXPERIMENTS

The tests on the spindle error motion were carried using the commercial experimental equipment. The measurement results were processed both using commercial program and software created accordingly to the algorithm described in [5], and briefly recalled above - Analyzer of Spindle Error Movements (ASEM). First of all, spindle rotational speeds measured by both programs and were different in two programs and were also different than the value displayed by the CNC controller. Therefore an independent sensor was used and the indexing marker was placed on the spindle. Independent measurements showed that the calculation of the spindle rotational speed based on the sensor X indications in ASEM program, were accurate. The software also performed the measurements of error motions without any problems. The repeatability of spindle speed determination in commercial program was unsatisfactory. With standard setting the results of rotational speed were changing in spite of the stable sensor indication.

a)
SPINDLE ERROR ANALYZER REPORT

RPM	Total	Sync	Async
504	47,8	40,0	46,9
999	4,1	1,9	2,6
1500	4,4	2,2	3,5
2000	5,1	1,6	4,3
2507	5,9	1,7	5,1
3013	5,3	2,5	4,4
3523	7,1	1,8	6,5
4021	7,0	1,7	5,8
4524	10,5	7,1	4,5
5032	8,6	5,1	3,7
5536	10,0	7,1	6,5
5991	11,4	7,5	5,3

b)
ASEM REPORT

RPM	Total	Sync	Async
501,3	5,1	1,7	4,2
999,8	5,3	1,6	4,2
1500,5	5,5	1,2	4,4
2001,6	6,0	1,2	4,7
2507,9	6,4	1,4	5,3
3013,3	8,4	1,9	6,3
3518,0	8,1	1,6	6,4
4023,2	9,6	2,1	7,7
4529,9	10,0	4,3	7,0
5037,8	9,9	2,2	6,6
5545,1	9,7	3,2	6,8
5999,7	9,0	3,8	6,7

Fig. 8. Comparison of the results   a) commercial b) ASEM software

Comparative studies of error motions were carried out both programs in automatic cycle. Spindle speed was set from 600rpm to 6000rpm with a step 200rpm and from 500rpm to 6000rpm with a step 500rpm. Each spindle speed was kept constant for 25 seconds. While the ASEM program performed fully automated measurements in the case of the commercial program, it was necessary to tune the system by setting the selected parameters. Since the machine tool has unstable rotational speed in the upper range, the first attempts of automatic measurements using the standard settings have failed.

The measurement results obtained from the both programs are different. Fig. 8 shows a screen with a summary of measurements in both programs.

It can be seen that the error motion values calculated by the commercial program are different than calculated by the ASEM program. This may be due to the fact that commercial software does not project the position of the measured point to the sensitive direction according to recommendation of the standards [1],[2]. A large value of errors computed by commercial software at 504rpm are the result of necessity to set the fixed parameters for the entire measured range. Setting spindle speed 500rpm was close to the minimum allowable rotation (488rpm).

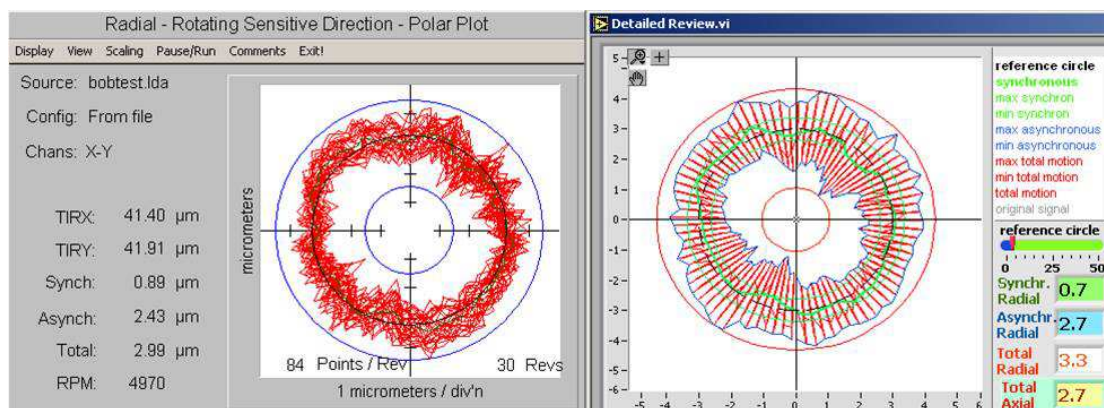Polar plots obtained from both programs are presented in Fig. 9.

Fig. 9. Results obtained with commercial (left) and ASEM (right) programs.

The plot obtained from the ASEM software with projection on the sensitive direction is much more clear and transparent. It has been noticed that the change of the rotation direction the commercial software does not show any significant changes in the polar plot. However, in the case of the ASEM software, such change of rotational direction causes radical change of the plot, making it practically unreadable as the rotation angle is taken the wrong way, due to wrong interpretation of X and Y axis (see eq. 1). The polar plot for CW and CCW directions, obtained from the commercial software shows in Fig. 10, from the ASEM software in Fig. 11.

According to the equation (1) plot after the changing direction of the spindle rotation, should be entirely different from the plot in the reverse direction. The coordinates of the exact point are measured first by the X sensor and next by Y sensor. In the case of CW angle between these sensors is 90°. However, in the case of reverse rotation (CCW) the
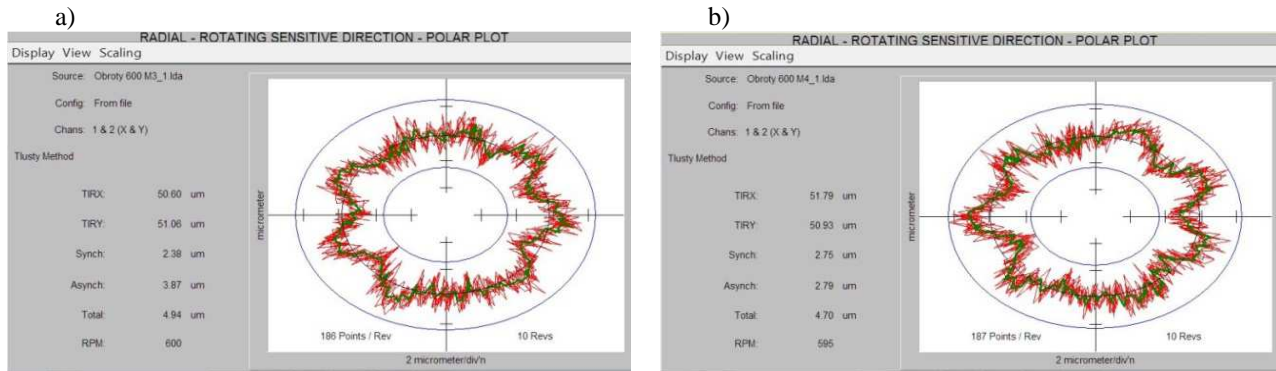
a)   b)

Fig. 10. Polar plots – commercial   a) CW   b) CCW

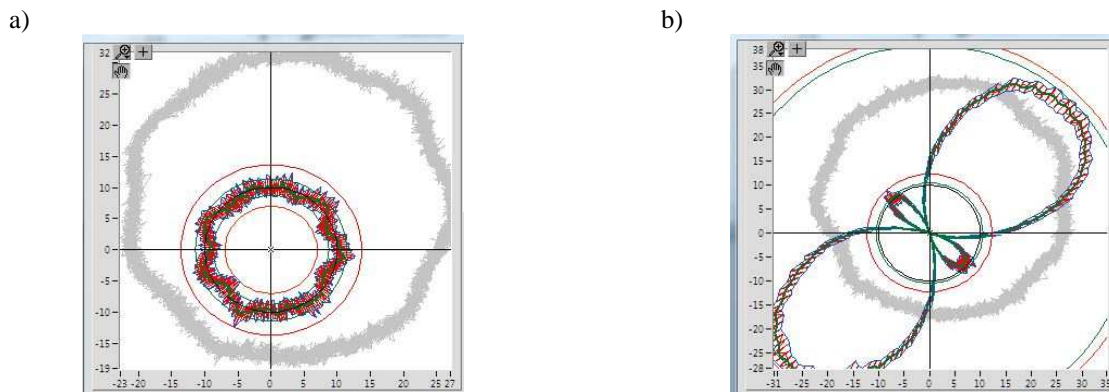a)   b)

Fig. 11. Polar plots – ASEM a) CW   b) CCW

angle is 270°. Plots may not be similar when measured in the direction of CW and CCW. Thus the plot created by the ASEM software is correct and this indicates that the X and Y position sensors are measuring the same angle position of the target. In contrast, commercial software makes measuring the sensors X and Y, but not necessarily in the same angular position and does not project the results on the sensitive direction.

6. CONCLUSION

The spindle error motion measurement becomes more and more popular, as its importance is appreciated by the industry. Commercial equipment for spindle error measurement is very high quality and designed, reasonably concerning construction and ergonomics. The commercial program has many options, settings and considerable measure possibilities (e.g. thermal deformation errors, or direct connection to a spindle encoder). Nevertheless, using it requires the knowledge of measurement, acquisition, and a data transfer. On the other side correctness of calculation methods and algorithms can be questioned. Apparently they do not follow the standard recommendations ignoring taking into account sensitive and no-sensitive direction. But it does not change the fact, that they

are still useful for diagnostics of the machine tool spindles. The change of the spindle state can be reflected in the increase calculated values by the program.

The ASEM program and applied algorithms define the spindle error motions in a much more accurate way. The developed software works automatically, measures rotational speed, and sets the proper sampling frequency. An average educated technician is practically able to carry-out measurements.

ACKLOWLEDGMENTS

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