Detection Method of Machine Tool Axis Offset Distance Based on Rough Set Neural Network

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Abstract. In the traditional detection method of machine tool mechanical shaft offset, the detection results fluctuate greatly. Therefore, a detection method of machine tool shaft offset based on rough set neural network is proposed. When the precision is not up to the standard, the influence of the installation error can be judged, and the space structure model of the mechanical axis can be established. The modified model of rough set neural network is used to get the theoretical value of the mechanical axis, measure the actual position of the mechanical axis, calculate the difference between the theoretical value and the measured value and get the offset distance. Experimental results show that this design method can reduce the fluctuation of detection results and the detection results are more stable than the traditional methods.

Keywords: Mechanical shaft · Offset distance · Neural network · Ball-Bar instrument

1 Introduction

As the carrier of advanced manufacturing technology and the basic means of production of equipment industry, the development level of machine tool is related to the development of many industries such as automobile, military industry, agricultural machinery, engineering machinery, electric power equipment, railway locomotive, ship and so on. Therefore, it is of great significance to study the method of measuring the offset distance of machine tool mechanical shaft [1]. At present, there are two methods to measure the offset distance: direct method and indirect method. The direct method uses precision testing equipment to measure the error of machine tool, and gives the precision index of machine tool directly in the course of measuring. With the improvement of testing methods and equipments, many new testing equipments have been developed, such as ball bar meter, laser interferometer, spindle rotary error analyzer and so on. These testing instruments and testing methods are mostly aimed at static precision or single axis precision measurement [2]. Indirect method is used to test the precision of the machine tool's mechanical shaft by using precision measuring instrument. The geometric precision, positioning precision, reverse clearance, five-axis interpolation precision, multi-axis linkage precision and rigidity vibration of the machine tool can be accurately

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reflected by evaluating the machining quality of the specimen, such as over-cutting, under-cutting, vibro-vibration and surface quality.

On the basis of the above theory, the detection method of machine tool axis offset based on rough set neural network is proposed. The RENISHAW ballbar is used to measure the error movement of the mechanical shaft. Based on this mechanical axis installation error is calculated. According to the calculated installation error, the spatial structure model of the mechanical shaft is constructed.

2 Detection Method of Machine Tool Axis Offset Distance Based on Rough Set Neural Network

2.1 Determination of Precision Specifications for Machine Tool Mechanical Shafts

The sample data is analyzed, and then an initial information table is formed according to the domain knowledge known. A reasonable discrete method is used to discretize the continuous attributes. A parallel reduction algorithm based on genetic algorithms is used to quickly reduce the attributes of the data. The reduced attributes are used as input layer neurons, and then the data is reduced vertically, including the elimination of inconsistent objects and redundant objects in the data, and finally a neural network is used to train the processed reduced data. The introduction of parallel reduction algorithms can further improve the overall mining efficiency of rough set and neural network models.

Select reasonable testing equipment, determine the accuracy of machine tool machinery shaft specifications. Select RENISHAW ball and bar instrument and Lion rotary shaft error analyzer, RENISHAW ball and bar instrument is mainly composed of ball and bar instrument testing equipment, variable length rod group, calibration gauge, machine tool installation components, etc., can be used for machine tool circular track accuracy and absolute length testing, mainly used for measuring the position and direction error between the machine tool axes [3]. The Lion Axis Error Analyzer is composed of capacitive displacement sensor, precision double standard ball, sensor base, 3-D pan and data acquisition sensor, which can measure the DOF motion error. The technical parameters of the club are as Table 1:

Table 1. Technical parameters of club instrument

Parameter	Numerical value	Parameter	Numerical value
Model	Qc2o-w	Sensor travel	1.75 mm
Sensor resolution	0.1 um	Maximum sampling rate and transmission range	1000 Hz
Measurement accuracy of ball and stick instrument	3%	Standard length	100 mm
Measuring range of ball and club instrument	±0.1 mm	Variable length rod group	50 mm

The technical parameters of spindle error analyzer are shown in Table 2.

Table 2. Technical parameters of spindle error analyzer

Parameter	Numerical value	Parameter	Numerical value
Host	5 displacement Channel	Displacement probe size	8 × 9 mm
Measuring range of displacement probe	75 um	Effective sensing area of displacement probe	2 mm
Nonlinearity of displacement probe	0.075 um	Standard ball size and roundness	50 nm
Resolving power	5 nm	Maximum speed	40000 rpm

The main body of the ball bar instrument is a high-precision telescopic linear sensor and two precision balls, forming a motion chain. The specific structure is shown in Fig. 1.

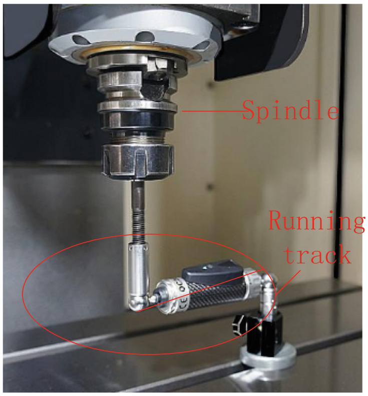

Fig. 1. Mechanical shaft structure

The two precision balls are respectively connected to the frame and the workpiece to be measured through the magnetic seat, and the distance between the two ball centers is read out by the displacement sensor. Measure the movement of the mechanical axis with the ball bar instrument, fix the ball bar instrument on the worktable, and make it pass through the mechanical axis, and install it on the mechanical axis to be measured, so as to complete the radial installation and axial installation of the ball bar instrument, corresponding to the axial and radial error sensitive directions respectively. In the ideal state, when the moving ball is installed in the radial direction, it is a circle with the center on the mechanical axis. When the ball is installed in the axial direction, it is a point on the mechanical axis. The measured value of the ball is the fixed value. Because of the error movement of the mechanical axis, the measured value of the ball is very close to the ideal value. Therefore, the measurement results of the two installations can directly reflect the radial and axial accuracy of the mechanical axis [4]. So far, the accuracy specification of machine tool mechanical axis is determined.

2.2 Installation Error of Mechanical Shaft of Computer Bed

When the accuracy of mechanical axis of machine tool cannot reach the specified standard, it is necessary to calculate the installation error of mechanical axis to determine the offset of mechanical axis. In the circle test mode, the running track of the machine tool is set as an arc, and the small change of the radius of the ball bar instrument in motion is measured by the sensor. Rough neural network is used for the analysis of arc trajectory. To determine the main error performance of the machine tool. The ball bar instrument is connected to the workbench and the spindle with the moving mechanical axis of the machine tool as the center, so that the ball bar instrument can do circular motion in a fixed coordinate system, and the ideal situation is recorded Due to the installation error of the machine tool mechanical axis and the ball bar instrument, the measured value of the ball bar instrument will deviate from the ideal value. Therefore, in the measured value of the ball bar instrument, the machine tool errors such as reverse clearance, reverse overshoot, non perpendicularity and proportion mismatch can be identified [5].

When there is installation error, the measurement data of the ball bar instrument will have sinusoidal characteristics. The mathematical model of the installation error of the ball bar instrument in plane test is established. An iterative least square method is used to eliminate the installation eccentricity. The motion of the ball bar instrument is assumed to be plane motion, so that the installation error of the ball bar instrument is equivalent to the center deviation. At this time, the least square circle fitting is used to eliminate the installation eccentricity of the ball bar instrument. The coordinates calculated by the rough neural network are $(\mathrm{x}_1, \mathrm{x}_2)$ of the mechanical shaft is:

$$\begin{cases} \mathrm{x} = \mathrm{r}\cos\theta \\ \mathrm{y} = \mathrm{r}\sin\theta \end{cases} \tag{1}$$

Among them, r is the radius of the club and θ is the angle of moving center. Based on the measured data of eliminating eccentricity, the other error items can be identified, such as ratio mismatch, verticality, reverse overshoot and reverse clearance, etc. Then the difference between the measured value of the instrument and the calibration length of the instrument is calculated and projected to two orthogonal coordinate axes to obtain the error component of a single axis. Finally, the mechanical axis is in the state of reverse overshoot. When the machine tool moves in a certain direction, the mechanical axis starts to decelerate and drive in the opposite direction when the set trajectory reaches the maximum stroke, a short stagnation will occur on the mechanical axis, and a spike will occur on the measured value of the ball-bar instrument. At this point, the machine tool mechanical shaft installation error calculation.

2.3 Construction of Mechanical Axis Spatial Structure Model

After eliminating the installation error of the mechanical shaft, the spatial structure model of the mechanical shaft is established. The precision of the mechanical axis is expressed by the radial and axial runout of the rotor, but the run-out is affected by the geometric error of the measuring surface and the installation position of the sensor and the workpiece. Since the motion of the ball-bar instrument is a space motion in the process of precision test, the measurement data is closely related to the installation position of the ball-bar instrument. Therefore, it is necessary to establish a mathematical model of the mechanical axis measured by the ball-bar instrument that is not affected by the installation error, and construct the space structure model measured by the ball-bar instrument with a single mechanical axis object. From the measurement data of the ball-bar instrument, the installation error of the ball-bar instrument and the mechanical axis is identified, and the relationship between the offset distance and the installation error is analyzed [6].

According to the three kinds of theoretical solutions of the ball bar instrument, the mechanical shaft structure models satisfying three kinds of conditions are obtained. Otherwise, it is very difficult to measure the mechanical axis accurately in the actual measurement. In the process of measuring the mechanical axis, the spatial structure model is used to analyze the data. In this case, the center point of the fixed ball is not on the axis of the machine, a partial conic surface can be obtained, and the spatial position data of the mechanical axis can be obtained. The third is that when the rotor of the mechanical axis rotates around the axis of rotation, there still exists the error motion relative to the fixed coordinate system, that is, the measurement data contains the error of rotation of the mechanical axis, and the error of rotation can be reflected by the theoretical value of the measurement data and the degree of the installation error of the ball-bar instrument. In this case, the measured value is regarded as the approximate axis of rotation, and the reference point of the fixed coordinate is obtained to rotate along with the mechanical axis, so the space structure model constructed takes the distance change of the reference point into account. Based on the above theoretical analysis, a spatial structure model is established to determine the theoretical installation value of the mechanical shaft by eliminating the measurement results of the ball and bar instrument. The rotary error value of the rotor of the mechanical shaft is much less than the theoretical output value, and the theoretical output value can be optimized through a minimum maximum value, and be identified from the measurement data. The final calculation formula of the spatial structure model d is as follows:

$$\mathrm{d} = \sqrt{\frac{L_1^2 + L_2^2 + h^2}{2L_1 \mathrm{hcos}(\vartheta_1 + \vartheta_2)}} \tag{2}$$

Among them, $L_1,\ L_2$ is the measured value and theoretical value of the length of the ball-bar instrument, h is the installation height of the machine tool shaft, and $\vartheta_1,\ \vartheta_2$ is the minimum and maximum of the rotating error of the machine shaft. Thus the construction of the mechanical axis spatial structure model is completed.

2.4 Revision Model Based on Rough Set Neural Network

The model error is corrected by iterating d values of rough set neural network. Taking formula (2) as the objective function of rough set neural network, the neural network has two advantages, weight sharing and local connection. By the requirement of local connection, the network connects the neurons in the network with those in the upper layer only, reduces several parameters of order of magnitude, and speeds up the correction efficiency. While weight sharing is based on the local connection, each neuron can use the same weight and further reduce the training parameters. The selected neural network has a feedforward network structure, and can train the model of spatial structure by making use of its advantage of local connection. It is known that the training of neural network of rough set includes two stages, forward propagation stage and back propagation stage, in which forward propagation is the process of transmitting data from low level space to high level space, and the output results after convolution layer, pooling layer and local connection layer are obtained when the input data is propagated forward, and the error between the output value and the target value is calculated [7]. The back-propagation is due to the deviation from the expected value of the results obtained from the forward propagation. Therefore, the training of propagation from the higher level to the lower level is adopted. Assuming that the propagation error of the preceding item is large, the gradient descent method is adopted to calculate the error between the actual value and the expected value in the back-propagation, and the error is back-propagated from the local connection layer to the middle pooled layer and convolution layer to the input layer [8]. The specific flow is shown in Fig. 2:

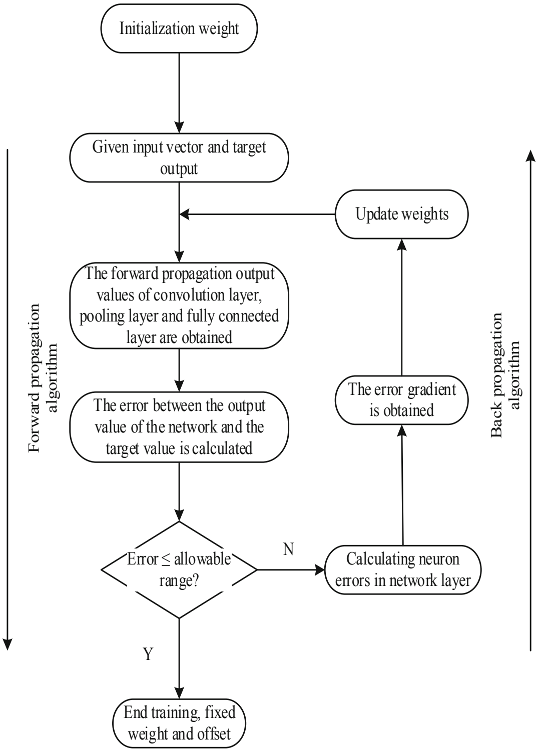

Fig. 2. Model updating process based on rough set neural network

After the neural network outputs the objective function, the final spatial structure model is analyzed. The fixed center of the ball and moving center of the ball have no axial installation error, and the measured value of the ball bar instrument can show the radial distance and axial distance. Thus, the spatial structure model of mechanical axis is modified based on rough set neural network.

2.5 Measurement of Actual Deviation of Mechanical Center Axis

The output value of the spatial structure model is taken as the theoretical value of the machine tool axis. On this basis, the actual spatial coordinates of the central axis are measured and the deviation between the actual value and the theoretical value is calculated.

2.6 Prediction of Mechanical Shaft Installation Position Parameters

In view of the actual value of the mechanical shaft, the same instrument is used to measure. The precision ball is fixed between the seats of the precision magnetic bowl by mechanical positioning, so that one of the magnetic bowl seats is connected with the machine tool worktable, and the other is connected on the machine tool mechanical axle and the machine axle box. When the distance between the two precision balls changes, the sensor of the ball bar instrument can accurately measure the change. When there is an error in the machine tool, the ball bar instrument can measure the circle track of the actual machining, and compare it with the theoretical track, so as to obtain the overall evaluation of the precision of the machine tool. Through the testing device of ball-bar instrument, the 4 steps error testing mode is put forward, and compared with the spatial structure model, the geometric error identification of mechanical axis is realized. Then the dynamic performance of the machine tool is determined by measuring the circular track of the biaxial linkage with a ball-bar instrument, and the linear error in one direction is obtained in one measurement.

The main task of the pre-measurement is to adjust the mechanical axis of each accelerator so as to minimize the deviation between the magnetic field axis and the mechanical axis. The pre-measurement must go through the following three steps: the calibration of a single component—the axis of a component is used as the x axis, the above the component is used as the y axis, the direction of the vertical plane is used as the z axis, and a component coordinate system is obtained. The spatial coordinates of the mechanical axis in the component coordinate system are determined by using the SMX4500 laser tracker. The spatial coordinates of the mechanical axis are measured by using the SMX4500 laser tracker. The determination of the coordinate of the datum—using the SMX4500 laser tracker to measure the four datums installed on the datum platform, including the faces, lines and points composed of the datum system, establishing the datum coordinate system, transforming the calibration points of the mechanical axis into the values under the datum system, and installing the standard values. The spatial position of the mechanical axis—the prediction of the mechanical axis—uses the SMX4500 laser tracker to adjust the coordinates of the component system and the datum system, so that the two coordinate systems of the parallel system are connected closely with the previous component system, and thus obtaining the position of the X axis and the predicted parameters of the mechanical axis. At this point, the mechanical shaft installation position parameters are predicted.

2.7 Measurement of the Actual Position of the Machine Tool Mechanical Shaft

According to the spatial position parameters, the mechanical shaft is precisely aligned and the actual position of the machine tool is measured. Based on the linear induction accelerator and laser tracker, the space position coordinates of the mechanical axis can be measured by a single station, and the precision can meet the requirement of high precision measurement of machine tool. In the tens of meters range of the linear induction accelerator, 7 stations are set up in 7 sections, each station measures 5 points, 35 points in total, so that the longitudinal measuring points cover the full length of the mechanical axis, and the measuring data can be obtained in both elevation and transverse aspects. According to the datum of linear induction accelerator installation, the datum coordinate system of precise alignment of mechanical axis is determined by setting up a good measuring control network. In the process of precise alignment of machine tool axis, through data processing, the value of component reference point in the calibration coordinate system is converted to the value in the overall installation coordinate system. The pre-collimated component datum is pushed to the space position of the mechanical axis, and the measuring platform is adjusted repeatedly so that the space coordinate system and the datum coordinate system are parallel until the whole accelerator is installed and the precision specification of the mechanical axis measurement is achieved [10].

After the reference points are arranged, the actual space coordinates after the mechanical axis alignment are measured. Because the photons of the acquisition point and the incident point of the laser beam are randomly migrated in the medium, Raman scattering photons are generated in the inner depth of the laser beam. Raman scattering photons are easier to be transversely migrated in the diffusion process. Therefore, the Raman spectrum deviating from the laser beam incident point at different distances contains the Raman spectrum information of different depth layers. When the spatial offset is 0, the maximum photon density of the laser beam is obtained. The Raman spectrum is mainly obtained from the mechanical axis. When the spatial offset is not 0, the Raman scattering contribution from the mechanical axis is larger. Raman fluorescence and Raman scattering from the mechanical axis is gradually reduced. However, it is not possible to completely eliminate the Raman spectrum from the original optical spectrum. Raman spectrum of the mechanical axis cannot be obtained directly in the original spectrum. Raman spectrum of the mechanical axis needs to be extracted by proper data processing method. After the spectrum is extracted, a 70 mm plane grating is placed on the horizontal double rotary table, and a reading head is installed at the end of the machine tool shaft. The gap between the reading head and the grating is measured. The laser interferometer can only measure the linear motion, but also can improve the measurement accuracy, and the final measurement result can be used to measure any trajectory in 2D plane, so that the actual position of machine tool can be measured. The deviation between the theoretical value and the measured value of the mechanical shaft is calculated, and the offset distance of the mechanical shaft is obtained.

3 Experiment and Analysis

The design method was recorded as experimental group A, and two traditional offset distance detection methods were recorded as experimental group B and group C. In the same experimental environment, the detection efficiency and stability of the three groups of methods are compared.

Three axes machining center is driven by three servo motors, X, Y to realize the working table, the principal axis of the mechanical axis to realize Z to linear feed movement. The machine tool parameters for a three-axis machining center are shown in Table 3:

Table 3. Machine parameters

	Minimum value	Maximum	Full stroke
Machine stroke X-axis	10 mm	410 mm	420 mm
Machine stroke y-axis	10 mm	310 mm	320 mm
Machine tool stroke Z axis	10 mm	– 220 mm	230 mm
Feed rate	0	5000 mm/s	5000 mm/s
Accelerate	0	2500 mm^2/s	2500 mm^2/s

The ball bar instrument is accurately installed on the workbench. The center lines of the two ball centers of the ball bar instrument are parallel to the plane of the workbench in the measurement process. The plane of the workbench is called the imaginary plane, and the ball bar instrument is installed on the imaginary plane as accurately as possible. In the actual operation of group A, in order to measure the spatial shift Raman spectrum, the experimental device of spatial shift Raman spectrum is built as shown in Fig. 3.

The laser is connected to the excitation probe by optical fiber, the working distance of the probe is 7.5 mm, the size of the laser spot converging on the surface of the mechanical axis is 200 um, and the generated Raman light is connected to the incident slit of the spectrometer through the collection probe, the working distance of the probe is 10mm, and the laser used is the SPLER-LAS785 of the spectrum laser photovoltaic, the wavelength is 785 nm, the continuous output power is 0–500 mW, and the linewidth is less than 0.2 nm. The spectrometer used is OE650JHG spectrometer with a slit width of 50um and a working spectral range of 651–879 um. For 785nm incident laser, the corresponding range of Raman frequency shift is –2662.1 –983.7 cm^{-1}. The focal point of the excitation probe and the collection probe are both on the surface of the mechanical axis. The excitation probe and the collection probe are fixed on the six-dimensional optical adjusting frame to adjust the different space offset distance. The offset distance that can be adjusted by the probe in the experimental device is –1.0–1.0mm. When the offset is zero, it is the working mode of the Raman spectrometer.

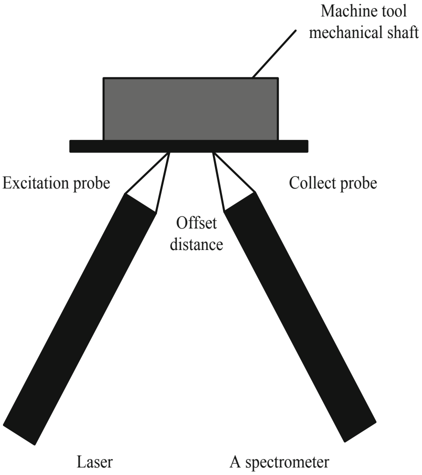

Fig. 3. Space migration experimental facility

3.1 Experimental Results

To change the testing radius of the machine tool, count the deviation testing results of the three groups of methods on the X direction and Y direction of the mechanical axis, compare the stability of the deviation testing values of the three groups of methods, and select the testing items of the offset distance as XY non-perpendicularity and XY inverse overshoot. The experimental comparison results are shown in Table 4:

Table 4. XY comparison of nonperpendicularity stability

Test radius of machine tool (mm)	Group A test results (Urad)	Group B test results (Urad)	Group C test results (Urad)
100	25.5	23.9	21.2
110	24.9	26.8	22.4
120	25.3	22.5	25.8
130	24.7	25.8	26.2
140	25.2	24.1	25.6
150	25.8	25.3	23.9
160	24.1	26.1	26.3
170	24.5	23.0	22.5
180	25.0	22.3	21.9

It can be seen from Table 5 that when the test radius of machine tool circle is changed, the detection value of mechanical axis offset distance in group A is more stable, the measured value of the mechanical axis offset distance of experiment group A fluctuates

Table 5. Comparison results of XY reverse overshoot stability

Test radius of machine tool (mm)	Group A test results (Urad)	Group B test results (Urad)	Group C test results (Urad)
100	5.5	3.9	1.9
110	4.9	6.8	2.1
120	5.3	2.5	5.2
130	4.7	5.8	6.3
140	5.2	4.1	5.8
150	5.8	5.3	4.2
160	4.1	6.1	2.9
170	4.5	3.0	2.2
180	5.0	2.3	3.1

slightly, while the detection results in group B and group C fluctuate greatly. On the basis of the first group of experiments, the detection time of the three groups of methods was compared. The experimental results are shown in Table 6.

Table 6. Comparison results of offset distance detection time

Test radius of machine tool (mm)	Test time of group A (s)	Test time of group B (s)	Test time of group C (s)
100	2.31	5.38	6.29
110	2.83	5.29	6.29
120	2.83	5.27	6.30
130	2.03	5.28	6.28
140	2.18	5.29	6.12
150	2.93	5.93	6.82
160	2.18	5.92	6.29
170	2.03	5.02	6.03
180	2.18	5.28	6.17

When the test radius of machine tool circle is changed, the detection time of mechanical axis offset distance in group A is significantly less than that in group B and group C, and the detection time can be as low as 2.03 s. This is mainly because the method in this paper uses neural network to modify the parameters in the model. To sum up, compared with the traditional method, this design method can ensure the detection efficiency, and the detection result is more stable, which ensures the accuracy of the offset distance detection value.

4 Conclusion

This design method gives full play to the advantages of rough set neural network and reduces the fluctuation of offset detection value. However, there are still some shortcomings in this study. In actual measurement, the trajectory of the moving ball center is not a circle, but a spatial curve. In the future research, the motion error of the rotary pair will be further eliminated.

References

1. Zhang, L., et al.: Application of laser trackers in the detection of concentricity and coaxiality—based on large water pipeline equipment. Indus. Technol. Innov. **7**(3), 108–112 (2020)
2. Wang, L., Zhang, S., Wang, D.: Geometric error measurement and accuracy verification of the swing head of a five-axis CNC machine tool with a single swing angle. J. Tsinghua Univ. (Sci. Technol.) **60**(4), 292–298 (2020)
3. Ma, T., et al.: Quantitative detection of off-Axis defects based on mode-converted waves with time of flight diffraction. Mater. Protect. **52**(9), 56-60+66 (2019)
4. Wei, L., Ding, K., Duan, Z.: Research on bearing workpiece detection and positioning based on Gaussian weighted mean segmentation. J. Electr. Measure. Instrum. **33**(10), 118–127 (2019)
5. Si, X., Bao, J.: Evaluate linearity error based on hill-climbing and differential evolutionary algorithm. J. Test Measure. Technol. **33**(5), 418-420+460 (2019)
6. Jianqiu, L.: Construction of real-time interactive mode-based online course live broadcast teaching platform for physical training. Int. J. Emerg. Technol. Learn. (IJET) **13**(06), 73 (2018)
7. Fu, W., Liu, S., Srivastava, G.: Optimization of big data scheduling in social networks. Entropy **21**(9), 902 (2019)
8. Liu, S., et al.: A fast fractal based compression for MRI images. IEEE Access **7**, 62412–62420 (2019)
9. Wang, R., et al.: Research on measurement method of optical coherence of transmitting and receiving infrared pulse laser range finder. J. Changchun Univ. Sci. Technol. **41**(1), 60–62 (2018)
10. Si, J., et al.: Simulation diagnosis for mechanical rolling bearing fault signal. Comput. Simul. **36**(1), 403–408 (2019)