

Reliability Oriented Performance Testing System of Chain-type Magazine and ATC

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Received: 21 May 2014 /Accepted: 31 July 2014 /Published: 31 August 2014

Abstract: Tool magazine and ATC (Automatic Tool Changer) are crucial functional components and the weak links of the fault locations of the CNC machining center. So the study on reliability of magazine and ATC is important to improve the reliability of machining center. The failure of magazine and ATC is a gradual progress from quantitative to qualitative, with the changes of some performance parameters (such as vibration, noise, position accuracy, etc.). To provide a test basis for the reliability growth technology based on performance parameters changing, a set of reliability oriented performance test system of chain-type magazine and ATC is developed. The testing of performance parameters such as the kinematical characteristic of manipulator, the magazine positioning error, vibration on the tool oriented part and noise is achieved. Then the developed reliability oriented performance test system of chain-type magazine and ATC is used to estimate the performance of chain-type magazine and ATC produced by Dalian Golden CNC Group Corp. The experimental data proves its feasibility. Under reasonable test time interval and performance parameters changing thresholds, this system will alert the operators to do some repairing in time when performance parameters degrade badly to prevent the failures effectively so as to avoid or decrease losses, then the reliability of magazine and ATC can be improved. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Chain-type magazine and ATC, Reliability, Performance test system, PSD, Positioning error.

1. Introduction

Tool magazine and ATC are crucial functional components and the weak links of the fault locations of the CNC machining center. According to relevant data, more than 50 % faults of CNC machining center are caused by tool magazine and ATC [1, 2]. Thus, it is important for improving the reliability of machining center to improve the reliability of tool magazine and ATC.

The Soviet Union is the first country to apply reliability technique to machine tools, and many

machine tool reliability researches have been done on the machine tool's structure, functions and external load action, finally some basic theories of reliability are built. America has done some tracking experiments on CNC machining center, collects and analyzes failure data to carry on reliability growth design [3]. A. Z. Keller and other scholars of University of Bradford in UK apply fuzzy theory to the analysis of CNC machine failure, and make some uncertain problems solved in quantity [4]. Some researchers of University of Birmingham in UK have kept track of thirty-five CNC machines and find that

CNC machine failure time obeys Weibull distribution [5]. Researchers in India apply genetic algorithm to the study of the reliability of the machine tool [6]. Germany is the best in the field of reliability of CNC machine, and manufacturers there pay attention to the feedback of operation failure of customers and apply reliability guarantee system to product manufacture, assembly and check [7]. Wang Yiqiang and other researchers of Zhejiang University in China analyze the failure of CNC machines on site and add information to failure database [8]. Due to the particularity of magazine and ATC's action, Xu Zhi tests the reliability of it and proposes improving measures to it by analyzing the results of the tests [9]. Based on the systematic research of chain-type magazine and manipulator's contingency screening and failure data analysis, Jin Yuanyuan and other researchers propose an early-stage contingency screening experiment method on the basis of environmental stress screening, and analyze the experiment results using FMECA method [10]. Ge Tian and other researchers use Duane model to design circular tool magazine and manipulator reliability growth experiments, improving the product reliability [11]. Hu Ye and other researchers in Jilin University set up a chain-type magazine reliability experimental platform and provide a method to account failure and analyze reliability [12].

The reliability analysis of tool magazine and ATC is still in early stages, most of which refer to mature CNC machine reliability research methods. Reliability oriented performance testing system of chain-type magazine and ATC has not been done. Chain-type magazine and ATC are repairable products, and the failure of magazine and ATC is a gradual progress from quantitative to qualitative with the changes of some performance parameters (such as vibration, noise, position accuracy, etc.). However, the changes cannot be detected easily, the experienced technicians used to listen to, hear and smell the changes. They judge the working condition of equipment by the changes of noise, temperature and smell, which is of low accuracy and hard to popularize. Some parameter changes of tool magazine and ATC are in regular connection with working conditions. With the development of modern measurement technology, control technology and signal analysis technology, those parameters can be detected accurately by testing equipment. After scientific signal analysis, a reasonable evaluation method of chain-type magazine and ATC can be formed. In order to provide a test basis for the reliability growth technology based on performance parameters changing, a set of reliability oriented performance test system of chain-type magazine and ATC is developed. Reasonable test time interval and performance parameters changing thresholds can be set properly with the help of this test system. Many performance tests and health condition evaluation of the tool magazine and ATC can be realized by this system. This system will alert the operators to do some repair in time when performance parameters

degrade badly to prevent the failures effectively so as to avoid or decrease losses. The breakdown maintenance of magazine and ATC can be changed into regular maintenance and even state maintenance level, so the reliability of magazine and ATC can be improved.

2. Tool Magazine and ATC Performance Test System Requisition Analysis

2.1. The Description on the Characteristics of the Studied Tool Magazine and ATC

The study object is the chain-type magazine and ATC produced by Dalian Golden CNC Group Corp (Fig. 1), which is mainly used in large horizontal machining centers. For LS-series magazine and ATC, the time of tool changing is 5 to 10 seconds, the maximum weight of a single tool is 30 kg, the magazine conveying speed is 20 to 30 meters per minute, and the maximum number of tools is 120.



Fig. 1. LS series chain-type magazine.

2.2. Test System Requirement Analysis

The test items of the designed reliability oriented performance test system of chain-type magazine and ATC are based on the major failures of magazine and ATC and mechanical industry standards of CNC machines. Much failure data of magazine and ATC has been collected by our group's acceleration test and customer's feedback. The causes of failure has been analyzed and summed up, and a list of major failure and its possibility of occurrence is showed as Table 1 below.

Table 1. Magazine and atc major failures.

Number	Position	Causes	Possibility of occurrence
1	ATC	Manipulator wrong movement	41.7 %
		Slotting tool failure	
		Drawing tool failure	
		Manipulator slipping the tool	
2	Magazine	Movement stuck	33.3 %
		Stop rotating	
3	Tool conveying mechanism	Much vibration on the tool oriented part	16.7 %
		Air cylinder failure	
4	Other parts	Motor and protective door failure	8.3 %

Judging from the Table 1, failure happens most frequently at ATC, then magazine and tool conveying mechanism. The causes of ATC failure are that manipulator does not move to the designed position and the poor dynamic performance of tool changing, such as manipulator's failure of slotting and drawing tools and wrong movement. The cause of dropping tool is the serious vibration of rotating, which makes the tool oriented part stuck and the servo motor stop. Tool conveying mechanism failure is caused by vibration and impact of tool oriented part or air cylinder failure. A great amount of failure information is contained in noise signal. According to the mechanical industry standard (JB/T10791.1-2007), the noise of a working CNC machine should be less than 75 dB, and the noise of magazine and ATC as a functional part of the whole machine should be less than 75 dB, too.

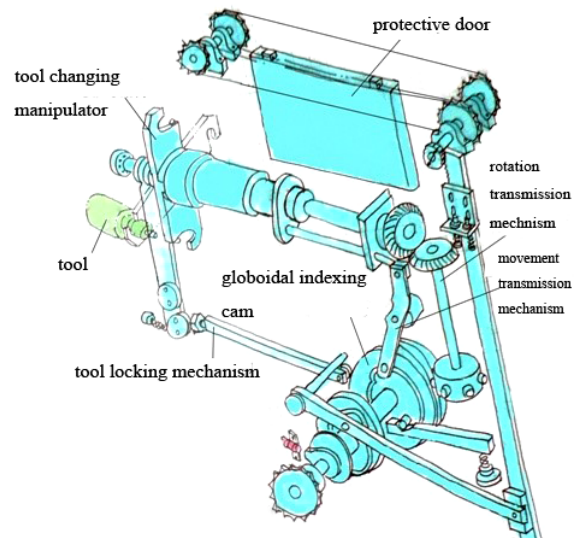
2.3. Test Requirements of the Manipulator's Angular Displacement, Axial Displacement and Acceleration

Mechanical cam linkage ATC and its transmission mechanism sketch, as shown in Fig. 2(a) and Fig. 2(b), displays how it works: an asynchronous motor drives an arc-surface cam, the rotation of manipulator is driven by a hexagonal roller, a pair of bevel gears and a spline pair, and the linear movement of manipulator is driven by an oscillating bar and a spline pair. Since arc-surface cam ATC has many power transmission links, the fit clearance is inevitable. The assembly process of arc-surface cam: firstly, rotate the assemble manipulator part to a certain position, then adjust the position of hexagonal roller and arc-surface cam, finally fix them

by ringfeder. However, such assembling method is of low accuracy and decided by the experience of workers, which causes the deviation of manipulator's angular displacement and linear displacement, including the wear of the cam. An effective way to avoid failure and improve reliability of ATC is to check the manipulator's angular displacement and linear displacement at reasonable intervals to get the degree of action deviation and repair it on time.



(a)



(b)

Fig. 2. Arc-surface ATC transmission mechanism.

In order to short the tool changing time, ATC accelerates as much as possible to reach top speed and brakes at maximum acceleration. Dynamic load and even impact may be caused by the great change of acceleration. What's more, the weight of two tools in the manipulator's two paws is usually different, and the additional resistance torque of manipulator at different positions is different, thus equivalent fluctuant load torque on motor is different. The

serious vibration of manipulator when changing tools is caused by all above. Such phenomenon is more obvious when there are not smooth gear meshing and much friction between moving parts. The tool dropping accidents and low reliability of transmission mechanisms are caused by serious vibration, dynamic load and impact. Therefore, it is crucial to test the acceleration during the movement of manipulator.

In conclusion, the movement of manipulator is the combination of linear and rotatory movement, so the angular displacement, linear displacement, tangential acceleration and axial acceleration of ATC manipulator should be tested.

2.4. Magazine Positioning Error Test Requirement

Magazine positioning error refers to the deviation between actual position and ideal position of tool pot. As it is shown in Fig. 3, under the control of numerical control system, the tool pot starts running at point O, and the ideal reaching position is point P, while actual reaching position is point P'. The vertical deviation of P and P' is called magazine positioning error.

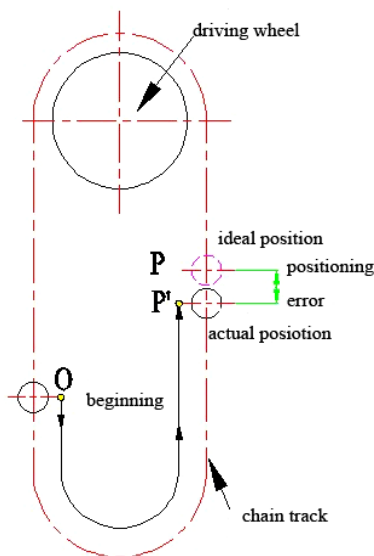


Fig. 3. Magazine positioning error sketch.

The reliability of magazine can be affected seriously by positioning error, which may result in positional deviation between a chain link and the tool oriented part at a tool changing position. When the tool pot is pushed in or drawn out of the tool oriented part by the air cylinder of tool conveying mechanism, crash between the tool pot and the tool oriented part may cause from violent vibration and loud noise to breakage of compression bar, damage of air pressure system and tool flying off. Increase of servo motor load torque, sometimes overload and motor protection stoppage, and even magazine stalling are

caused by the friction between loose tool chain and outer wall of track.

2.5. Test Requirement of Vibration on the Tool Oriented Part

Tool magazine and ATC conveying mechanism is composed of an air cylinder, a tool oriented part and a clamp moving on the guide track. The movement of a tool between tool changing position and manipulator's tool grasping position is realized by the tool oriented part. As it is shown in Fig. 4(a), the driving source is an air cylinder, the tool oriented part is gripped by a clamp, and the tool pot carrying tools are driven by the clamp fixed on the piston rod of the cylinder.

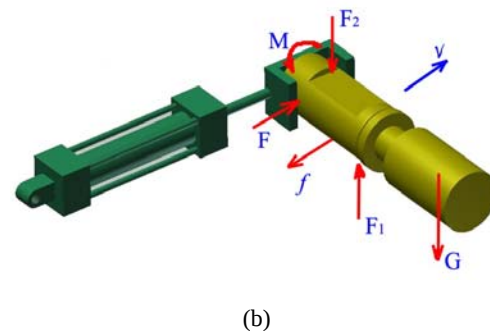
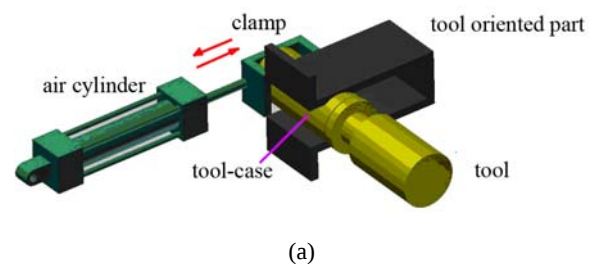


Fig. 4. Tools conveying process and force condition.

Vibration, impact, noise and magazine shaking are caused by uneven movement of tools in the chute of the tool oriented part. The uneven movement of tools in the chute of the tool oriented part is caused by unstable force condition during the tools' movement and dynamic load, as shown in Fig. 4(b). The output of the air cylinder is constant, however, since the difference of weight and length of tools, the friction force that each tool carries is different, so is the acceleration. At the end of the tool oriented part, the cylinder stops suddenly, impact caused by the crash of tool pot and end of the tool oriented part has negative effect on the lifetime of the tool pot. Furthermore, since the clearance fit of the tool pot and the tool oriented part, the creeping phenomenon of the tool pot occurs. And the driving torque fluctuates, which is an unstable load of the air cylinder. The reliability of air cylinder is influenced negatively. The intensity of vibration and impact

during the conveying process can be detected by detecting the vibration of the tool oriented part. The decrease of fixing device strength and even tool dropping accidents may be brought about by too much vibration and impact. The lifetime of the air cylinder is negatively affected by the unstable load. Reliability oriented performance test system of chain-type magazine and ATC is developed to test the vibration of the tool oriented part, get to know the vibration of tools of different weight, and evaluate the fitting condition of tool pot and tool oriented part. Some action can be taken to reduce vibration and impact and improve the reliability of magazine and ATC.

2.6. Noise Test Requirement

According to mechanical industry standard (JB/T10791.1-200), abnormal noise and impact should be avoided in high-precision machines, and sound pressure level of a continuous running machine should be less than 75 dB (A). Tool magazine and ATC are crucial functional components, and their noise levels should be less than 75 dB.

All in all, angular displacement, axial displacement and acceleration of the manipulator, magazine positioning error, vibration of tool oriented part and noise should be tested in the designed reliability oriented performance test system.

3. Overall Scheme Design

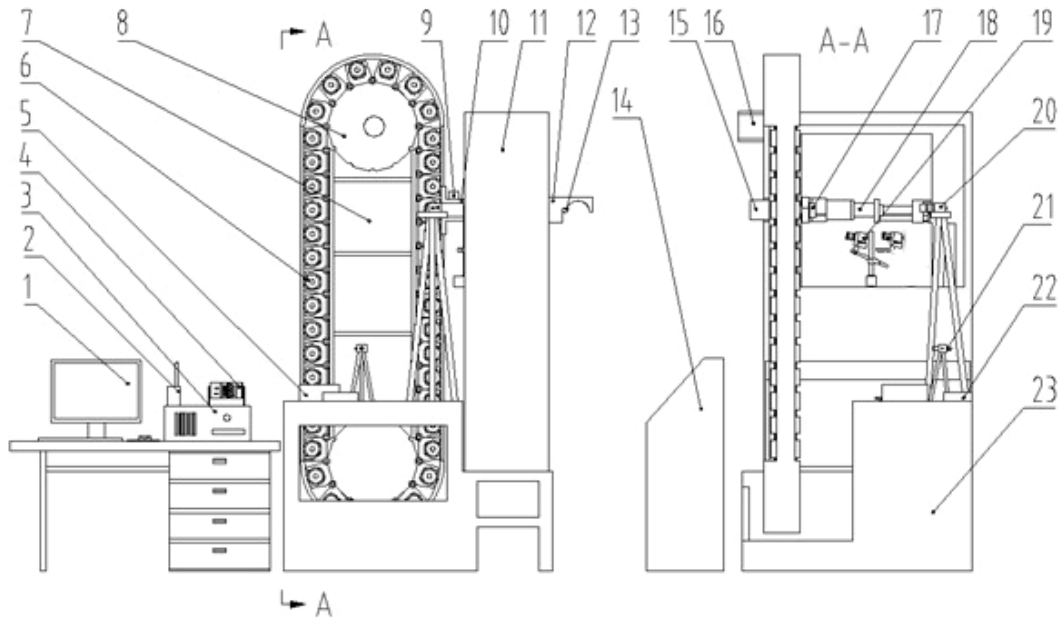
The overall scheme of the designed reliability oriented performance test system is shown in Fig. 5, including numerical control (NC) power unit, mechanical transmission unit and performance test unit. NC power unit is the key control and power element of the performance test system, including a servo motor that controls the rotation of magazine, an air cylinder that conveys tools and an asynchronous machine that drives the ATC. Selecting, grasping, changing tools and other complex mechanical action of magazine and ATC are under the control of NC ordered command control. The mechanical transmission unit is the power transmission part and end executor of the test system, including magazine transmission mechanism made up of a power sprocket and a tool chain, tool transmission mechanism composed of an air cylinder and a tool oriented part and ATC consisted of an arc-surface cam, a bevel gear pair and a manipulator. Performance test system is made up of many sensors, an industrial camera, a data acquisition card, an industrial computer, and relevant test software. Quantitative detection of performance of tool magazine and ATC and test reports can be accomplished.

The magazine and ATC test platform system is made up of numerical control power unit and mechanical transmission unit. Different types of magazines and ATCs can be tested on the platform. Performance test unit is the key part of the test system, using many contactless sensors which is easy to assemble and disassemble and is suitable for testing many types of products. A PSD based three-dimensional coordinate measuring instrument, a wireless acceleration sensor, a three-axis vibration sensor, an industrial camera and a sound pressure sensor are the detecting elements of the test system. An analog voltage acquisition card, an IEPE analog acquisition card, a gigabit-nic and a wireless gateway are used as data acquisition and transmission equipment. The process of test is controlled by the digital value input and output acquisition card, according to the operation status of magazine. Visual detection, digital filter, spectral analysis, image characteristics extraction and other signal processing and calculation functions are realized by the software.

4. Signal Acquisition and Transmission of Test System

Overall structure of reliability oriented performance test system of chain-type magazine and ATC is shown in Fig. 6. According to different types of signals, standalone channels are set to provide well-arranged structures and avoid interference of different signals.

In the test of angular rotation and axial shifts of ATC manipulator, a PSD based three-dimensional coordinate measuring instrument is developed to detect the high-power LED light installed on the arm of manipulator. The output voltage signal of PSD is transferred to an industrial computer by an analog voltage acquisition card. Meanwhile, control signal is sent by the industrial computer to a digital value input and output acquisition card. Working condition of the LED light is regulated by the industrial computer through a wireless data transmission module. The signals of manipulator acceleration are collected and transformed into analogue signals by a wireless acceleration sensor, and sent to the industrial computer after wireless gateway receiving the signals and A/D converting them. In the test of positioning error of magazine, the images of tool changing part is acquired by an industrial camera and transferred to the industrial computer by a gigabit-nic. In the test of the tool oriented part vibration, the vibration signal is converted into voltage signal by a three-axis vibration sensor, adjusted by a signal processor and sent to the industrial computer by an IEPE analog acquisition card. In the test of noise signals, a sound pressure sensor has the same transmission mode as vibration signals. Signal acquisition, processing and preservation functions are integrated in the software.



1 – monitor; 2 – wireless gateway; 3 – industrial computer; 4 – data acquisition card ; 5 – acceleration noise processor; 6 – tool pot; 7 – magazine main part; 8 – sprocket; 9 – three-axis acceleration sensor; 10 – tool oriented part; 11 – ATC box; 12 – manipulator; 13 – LED light; 14 – numerical control electricity cabinet; 15 – air cylinder; 16 – stepper motor; 17 – wireless vibration sensor; 18 – manipulator transmission axis; 19 – PSD sensor; 20 – industrial CCD camera; 21 – noise sensor; 22 – PSD signal processor; 23 – detection base.

Fig. 5. Overall structure of reliability oriented performance test system of chain-type magazine and ATC.

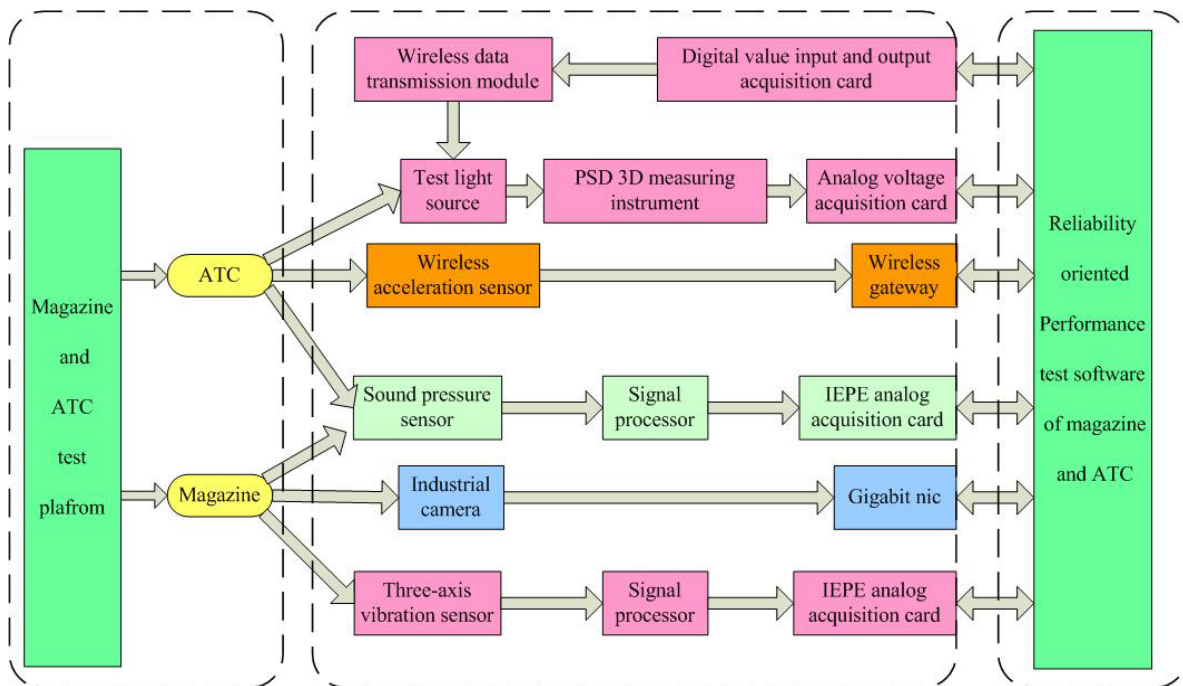


Fig. 6. Signal transmission and data acquisition structure chart of test system.

5. Development of System Software

The main program of reliability oriented performance test system of magazine and ATC is comprised of a test program, an auxiliary test program and a control program. According to the requirement of the test system, the angular rotation, axial shifts and acceleration of the manipulator,

magazine positioning error, vibration of the tool oriented part and noise are five parts of the test program.

The three-dimension calibration of the PSD based three-dimensional coordinate measuring instrument and the control of high-power LED light are included in the auxiliary test program and control program.

The program is mainly written by LabVIEW (Laboratory Virtual Instrument Engineering Workbench). The test system is divided into five individual parts, and five subordinate interfaces are linked to one main interface. The main interface is

well organized, which is used to synthetically display the overall performance and lead to different functional interfaces. The subordinate interfaces can be reached by pressing the left buttons, as shown in Fig. 7.

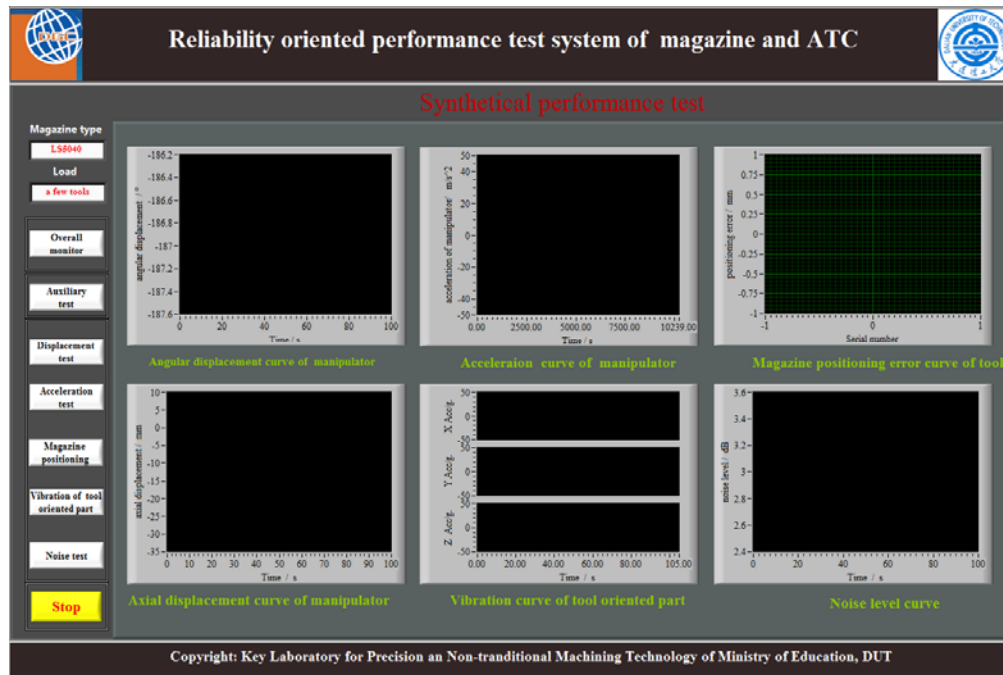


Fig. 7. The main interface of software.

6. System Experiment

Finally, this test system is applied to the test of chain-type magazine and ATC of Dalian Golden CNC Group Corp. The test results of angular rotation and axial shifts of manipulator are shown in Fig. 8 and Fig. 9.

Judging from Fig. 8, the angular rotation is stable in general, but the angular rotation between the initial position and the tool grasping position is not 90° . The deviation is about 8° , which may be caused by the assembly error. Judging from the axial shift of the manipulator, the shake of the manipulator when changing tools is very obvious, especially during the rotation of the manipulator, there is great axial play. More shakes can be seen in tool changing action than the tool grasping and returning position. Judging from both the angular rotation and axial shifts, there are axial shifts when the manipulator changes tools, which brings the peaks of axial shifts rising trend.

The acceleration of the manipulator is tested with tools on, and JM5840 wireless acceleration sensor is attached to the inside of the manipulator arm, near the tool paw. The tangential and axial acceleration curves in a period of tool changing are shown in Fig. 10 and Fig. 11. Since the spline pair of the manipulator is of good concentricity, there is not much run-out in rotation and linear shifts. It is of no research significance, since radical acceleration of the manipulator changes little.

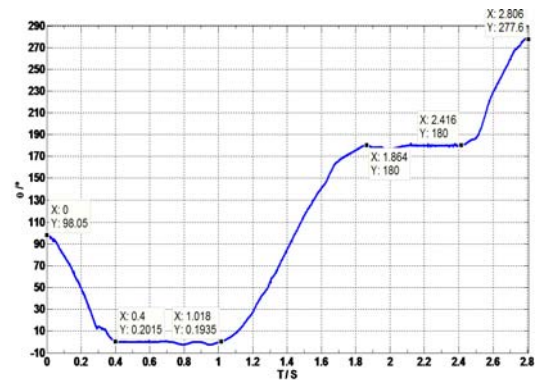


Fig. 8. Test result of angular rotation of the manipulator.



Fig. 9. Test results of axial shifts of the manipulator.

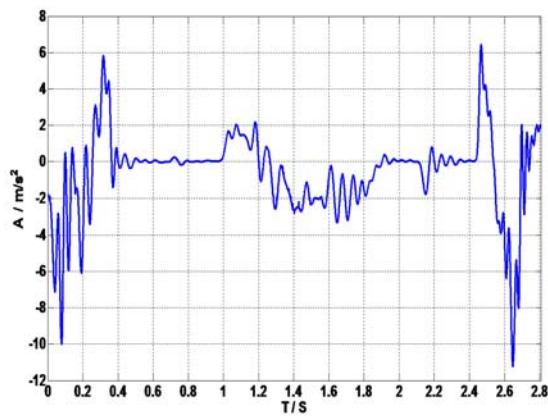


Fig. 10. Tangential acceleration curve of the manipulator.

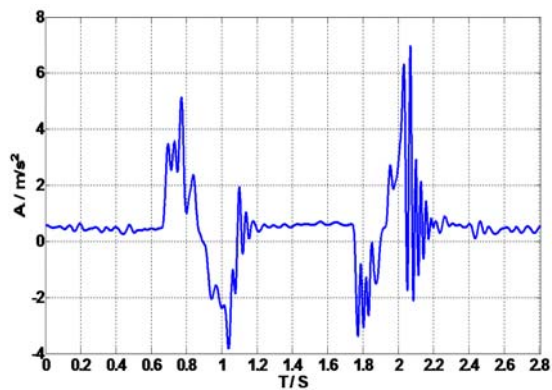


Fig. 11. Axial acceleration curve of the manipulator.

Judging from the measured data, it is obvious that fluctuation of the tangential and axial acceleration of the manipulator is very large, which is caused by the shake of the dynamic load. The tangential shake is mainly in the process of tools grapping and returning. The maximum acceleration of tool changing appears at the early-stage of tool grapping and the end of tool returning, namely at the moment of the quick start and stop of the manipulator. The axial shake appears primarily in the process of tool drawing and slotting, that is, there is creeping phenomenon of the manipulator in the process. What's more, the fluctuation of axial acceleration of the manipulator during the periods of tool grapping, changing and returning is attributed to the axial swing of the manipulator.

Eleven tool positions are selected to determine the magazine positioning error, and the measuring results are shown in Fig. 12.

In the eleven tests, the average deviation is 0.2776 mm, the maximum positive deviation is 1.0985 mm and minimum negative deviation is 0.0095 mm. The positive deviation indicates that the tool pot is below the ideal center position of tool guiding groove, while the negative deviation indicates that the tool pot is above the ideal center position of tool guiding groove. The more positive values are correspond to the tension of the upper chain and loose of the lower chain affected by gravity.

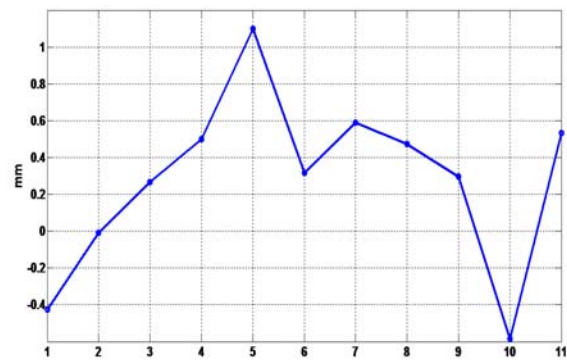


Fig. 12. Measurement of magazine positioning error.

The results of noise test are shown in Fig. 13. The noise of the magazine is the composition of many noise sources, which are mainly from the motor, transmission mechanism, magazine chain and movement protective door. Judging from the test results of sound pressure of the noise and actual operation state of the magazine and ATC, open and close of the protective door is the major source of noise. During the test, the maximum noise is 60 dB more or less; only few are more than 75 dB.

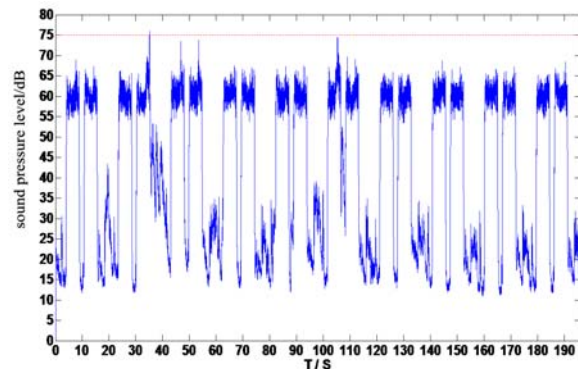


Fig. 13. Sound pressure grade signal of the noise.

7. Conclusions

On the basis of statistic data of magazine and ATC common failure, functional requirement analysis of reliability oriented performance test system of chain-type magazine and ATC is done. The objects of the test system are: angular rotation, axial shifts and acceleration of manipulator, magazine positioning error, vibration of tool oriented part and noise. An overall scheme of test system is worked out. Signal acquisition and overall transmission structure design of reliability oriented performance test system of chain-type magazine and ATC are achieved, as well as the hardware design which is mainly made up of sensors, data acquisition cards and an industrial computer. The hardware system of signal generation, conditioning and transmission is also realized. The software design of reliability oriented performance test system of chain-type

magazine and ATC is done on the development platform of LabVIEW combined with Matlab. Finally, tests have been done on the LS-series magazine and ATC produced by Dalian Golden CNC Group Corp, and the results are analyzed. The experimental data proves the feasibility of reliability oriented performance test system of chain-type magazine and ATC test system. With this test system, many performance parameters of magazine and ATC can be detected. When performance parameters degrade badly, it facilitates to prevent the failures effectively so as to avoid or decrease losses, and then the reliability of magazine and ATC can be improved. In order to describe the change rules of the performance parameters of magazine and ATC, a lot of experiments must be done at certain time intervals and more accurate evaluation methods need to be found according to experimental results.

Acknowledgements

The research is supported by the National Natural Science Foundation of China under Grant No. 51305061; the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20120041120034) and the Fundamental Research Funds for the Central Universities (No. DUT13LAB13). The financial contributions are gratefully acknowledged.

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