Dynamic Performance Analysis of the micro-hole EDM Machine Tool

Liu Jian-yong 1,2, Wang Min 3, Hu Jian-fei 1,2, Qin Peng 3, Shi Long 1,2*, Cai Yan-hua1,2

1 Beijing Institute of Electro-Machining, Beijing 100191, China
2 Beijing Key Laboratory of Electrical Discharge Machining Technology, Beijing 100191, China
3 Advanced Manufacturing technology of the Key Laboratory of Beijing Municipality, College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China
*Corresponding author’s e-mail: 875598674@qq.com

Abstract. The EDM machine is a special processing machine using the principle of EDM process of conductive materials. By means of modal analysis, ODS (Operational, Deflection, Shapes) analysis and order analysis, the static and dynamic performance parameters of the EDM machine tool are studied. According to the processing requirements, the structure of the machine tool is optimized, and the weak links are strengthened so as to reduce the aperture dispersion of the machined holes. Through the modal test experiment firstly analyzes the natural frequency, damping ratio and modal shape in each mode of machine tool structure to understanding the characteristics of each order machine main mode. Then, through ODS (Operational Deflection Shapes) test, it analyzes the vibration characteristics of machine tool structure in operation condition. And it also analyzes the relation-shape between the vibration of rotating machinery and the speed of the machine through the order analysis to predict the vibration of actual machine tool structure in a certain band external or internal variety of vibration response. Finally, it makes a comprehensive study on the static and dynamic performance of machine tools, and provides a reference for the design and optimization of structure dynamic strength.

1. INTRODUCTION
EDM machine tool is a special machine tool for processing conductive material by using EDM principle [1]. Because it has the characteristics of non-contact processing, no macroscopic cutting force, killing with kindness, precision micro etc, precision micro EDM technology has been widely used in aviation, aerospace, computer technology, instrumentation, precision machinery, automotive and other industries in some of the cutting-edge products [2,3].

The research object of this paper is the seven axis precision NC EDM machine tool developed by Beijing Institute of electrical processing [4,5]. The three dimensional diagram is shown in Figure 1. It is found that when the spindle speed reaches 1000 revolutions per minute, the machine tool will vibrate violently, resulting in a larger diameter difference of the machined holes, which will affect the quality of the machining. Therefore, through the experimental analysis, the structure of the machine tool is optimized, and the performance is improved, and the aperture difference of the hole is reduced.
Figure 1. Three-dimensional diagram of seven axis EDM machine tool

For example, 0.26mm tungsten wire is used to process metal plates of 1.25mm thickness. The ideal machining aperture is 0.3mm, and the diameter of the actually machined hole is shown in Figure 2. A total of 32 holes were machined, and the bore number was 1-32.

The maximum aperture difference of these holes is 0.014mm. Modal test and ODS analysis can be used to understand the mode of machine tool. According to the modal shape, the reference is put forward to optimize the structure and reduce the vibration of machine tool, so as to reduce the aperture difference.

The structure near the R axis of this machine tool needs to be analyzed in detail, therefore, a three-dimensional drawing of this part of the structure is drawn, as shown in figure 3.

2. Modal test

Mode is the inherent vibration characteristic of mechanical structure. Modal analysis is an important method for structural dynamic design and equipment fault diagnosis, and provides an effective way to study vibration of various practical structures. First of all, the machine tool is subjected to artificial vibration in the static state, and the transfer function between any two points is obtained by analyzing the two channel signal of the vibration force of the exciter and the vibration acceleration of the machine tool. Then, the modal parameters of the machine tool are identified by the curve fitting of the test transfer function. Finally, modal analysis theory is applied to solve the modal shapes of machine tools [6].

2.1 Test equipment

The modal experiment was carried out by the modal testing and analysis system of the B&K company of Denmark. The main test equipment include three direction acceleration sensor, 5320-50 type hammer, pulse system, 3560B data acquisition front end and so on. The measured frequency response function data is imported into ME'ScopeVES software to identify the modal parameters. In the
experiment, the impact hammer is used to shock the fixed excitation point. Because the striking force is grasped by people so it is difficult to control each time. In order to reduce the random error, each set of points should record 3 sets of data, which makes the frequency response function smoother. According to the correlation coefficient of frequency response function is good or bad judgment. In general, the closer the coherence coefficient is to 1, the smaller the experimental interference is, and the more reliable the experimental result is.

2.2 Selection of excitation mode and measuring point

Due to the smaller space of the tested machine tool, and the three direction force acceleration sensor requires the angle of the hammer striking direction is 45 degrees with the angle of the X, y and Z direction (the directions of X, y, and Z are consistent with figure 3). Because using a mobile sensor for multi-point pickup is more convenient and easier to guarantee the same angle, so the excitation mode of this modal experiment is single point excitation and multi-point vibration pickup. That is, in the experimental process, the excitation point is not changed and the position of the vibration pickup point is changed only. The hammer strikes the test specimen and gives it an impulse. The vibration signal is measured by an accelerometer mounted on a machine tool. The force signal and response signal are fed into the PULSE analyzer to calculate the frequency response function.

In order to stimulate various modes which affect the performance of machine tools under practical conditions, the excitation point is selected at the upper end of the R axis. The angle between excitation direction and the the x y and z directions are all 45 degrees. The sensors are respectively arranged on the bed, Y axis, C axis, column, Z axis, W axis and R axis. A total of 31 measuring points were selected in this experiment.

![Figure 4. Pick up points and exciting points position](image1)

![Figure 5. PULSE system test panel](image2)

2.3 Test procedure and results

According to the size of the machine tools, a wireframe model built for machine tool entities inside the Geometry. Because those points need to collect data, the direction of the points should be in accordance with the three direction force sensor.

Test the mode of the machine tool and the test system panel as shown in figure 5.

In the case of good coherence, save the results and import the results into the post-processing software ME'scopeVES for analysis. The modal parameters of the machine tool can be obtained, as shown in Table 1. The modal shapes are shown in Table 2, and the mode of operation is shown in figure 6. Because of the limited length of the article, only the first order vibration modes and the first five modal formation characteristics are listed.
Table 1. Modal parameters

| Modal order | Natural frequency (Hz) | Damping ratio (%) | Modal stiffness (N/m) |
|-------------|------------------------|-------------------|----------------------|
| 1           | 35.4                   | 1.88              | 355e6                |
| 2           | 54.7                   | 3.57              | 114e6                |
| 3           | 142                    | 3.28              | 3.27e9               |
| 4           | 191                    | 2.83              | 303e6                |
| 5           | 333                    | 1.42              | 529e6                |

Figure 6. Working mode of first order

Through the analysis of the vibration modes obtained by modal testing, it is found that when R axis is used the low dynamic stiffness of EDM machine tools is caused by the two order modes of natural frequency 54.7Hz, which is exactly 3 times the frequency of 1000rpm. By analyzing the working vibration modes of the machine tools, it is found that the low stiffness is caused by that the stiffness of the joint of the connecting plate and the bearing seat is poor. At the same time, through analysis of other main modal formation, it is found that the Q type stent is easy to produce Z direction vibration, and the joint surface of connecting plate and B axis also has the problem of unreliable connection. These are likely to restrict the improvement of the anti-vibration performance of the spindle of EDM machine tools.

Table 2. Modal formation and characteristics

| Modal order | Natural frequency (Hz) | Mode characteristic                                                                 |
|-------------|------------------------|-------------------------------------------------------------------------------------|
| 1           | 35.4                   | The connecting plate and the R axis vibrate in the Y direction.                     |
| 2           | 54.7                   | R axis and the connecting plate vibrated torsionally in the X-Y plane.              |
| 3           | 142                    | The connecting plate and the W axis vibrate violently in the x-z plane.             |
| 4           | 191                    | The B shaft motor is vibrating in the Z direction and the connecting plate drives the W shaft and the R shaft to vibrate violently in the x-z plane. |
| 5           | 333                    | The connecting plates vibrate violently in both the x-z plane and the Y-Z plane.    |

3. ODS test

ODS is defined as the analysis of vibration and deformation of a structure at a certain frequency, which indicates the vibration state of the structure under certain working conditions.
3.1 Test equipment
The test was conducted using the Danish B&K company's ODS test and analysis system. The main test equipment include 3 unidirectional acceleration sensors, 5320-50 force hammer, pulse system, 3560B data acquisition front end, etc. The measured frequency response function data is imported into ME'scopeVES software to identify the modal parameter identification. During the experiment, a sensor is fixed to a certain position, (the reference sensor is chosen to be fixed on the flange of the clamping electrode wire), The rest of the sensors are moving at the point of interest to obtain the signal. The ODS test was carried out under the condition of reciprocating feeding of the W axis.

3.2 Excitation mode and selection of measuring points
According to the shape, structure and mode shapes of machine tools, in the machine outside choose 8 pick-up points and reference pick-up points set in the upper edge of R axis. Due to the limited number of sensors (three), each test was conducted in four groups. Due to the limited number of sensors (three), each test was conducted in four groups. The sensor signal at the upper end of the R axis is determined as a reference signal (an excitation signal), and the remaining two sensor positions are moved until all the measuring points are measured. The layout of the measuring points is shown in figure 7.

3.3 Test procedure and results
This ODS carries on the experiment to the machine tool using the W axis feed processing. The sensor is inserted into the model and the direction of the sensor is adjusted. The machine tools are measured in three directions: X, Y and Z. The sensor position is shown in figure 7. Record the vibration and deformation of the machine tool in the three directions of X, Y and Z when feeding the W axis. After analyzing the experimental data into the post-processing software ME'scopeVES, the modal shapes of the machine tools can be obtained, as shown in figure 8. Because of the length of the article, only the first order modes of vibration are listed here. The natural frequencies in the three directions of X, Y and Z are shown in Table 3.

| Direction | 49.1 | 139 | 195 | 356 | 443 | 588 |
|-----------|------|-----|-----|-----|-----|-----|
| X direction | 50.3 | 115 | 207 | 328 | 485 | 615 |
| Y direction | 50.3 | 115 | 207 | 328 | 485 | 615 |
| Z direction | - | 150 | 210 | 371 | 474 | 685 |

Compared the experimental modal test results with the ODS test results it can be found that in the static state of the spindle, the excitation frequency has six orders, which is similar to the natural frequency. At this speed, chatter may occur near the six frequency ranges, which means that the six frequency components are more likely to be excited in the actual running state of the machine.
By comparing the vibration modes of ODS test with the modal test, it can be found that in the two experiments the larger deformation structures are the union surface of the B axis and the connecting plate, the connecting plate and the Q type bracket, including the bearing seat. Therefore, the results of the two experiments are consistent, indicating that the experimental results are credible and reliable.

4. Vibration order analysis
The vibration of rotating machinery is closely related to the speed of the machine. The mechanical axis of the mass imbalance and eccentric will cause vibration. Its vibration frequency is an integer multiple of the speed of revolution frequency. In addition, there is a transmission ratio between the active and the driven parts in the mechanical drive. Therefore, the vibration signal analysis is often based on the basic axis speed. The multiple relative to the base axis speed is called order. It is called order analysis that order speed is used as independent variable.

4.1 Test equipment
This order analysis experiment is conducted by the test and analysis system of the Danish B&K company. The main test equipment include 1 unidirectional acceleration sensors, 1 MM0024 infrared tachometer, pulse system, 3560B data acquisition front end, etc..

4.2 Test points selection
In actual conditions, the machine will cause noise and vibration when the R axis speed is known to be 1000rpm. Therefore, this vibration order analysis will set R axis speed as reference speed and an insulating black tape is coated on the flange surface at the lower part of the R axis, and put a reflective paper on the adhesive tape. Align the MM0024 infrared tachometer which is placed at about 30mm from the R axis to the lower flange surface of the R shaft. It fixed with a magnetic mount. The unidirectional acceleration sensor is arranged on the bearing seat, and since the vibration in the X direction is much larger than that in the Y direction, the sensor selects the direction of the X to be measured.

4.3 Test procedure and results
The reference speed is R axis speed, which is increased from 500rpm to 1800rpm by manual speed regulation. The pulse system will automatically draw the three-dimensional spectrum of vibration nephogram and order vibration nephogram.

The order spectrum of the vibration signal in the R axis X direction is shown in Figure 9. The X direction here is consistent with the X direction in ODS.

![Figure 9. vibration acceleration of X direction](image1)

![Figure 10. Vibration displacement of X direction](image2)

In Fig. 9, the abscissa is the order of the reference speed, the ordinate is the reference axis speed, and the color depth indicates the severity of the vibration acceleration. A number of vertical bright lines can be seen from Fig. 9, indicating that there exists a strong forced oscillation on a number of
orders with the spindle speed as the fundamental frequency. The order represented by these bright lines is shown in table 4.

| Order | 1 | 2 | 4 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|

The order of the maximum amplitude forced vibration is 2 order. The strength of the 1 order vibration is weaker. The vibrations of the 7, 8 and 9 order are low at low speed but when the speed increases to 1100rpm, the vibration intensity will increase by two to three times. The vibration intensity of the 2 order is the largest, and the main reason is that the R axis is driven by the motor through the belt, which drive ratio is 2. Therefore, the 2 order represents the forced vibration caused by the rotation of the motor.

The two order integral of Fig. 9 is used to obtain the order-displacement spectrum of vibration signal, as shown in Figure 10. The abscissa is the order of the reference speed, the ordinate is the reference axis speed, and the color depth indicates severity of the vibration displacement. As you can see from the diagram, the bright lights of the 1 and 2 order are still very large. Especially in the 2 order, the maximum value can reach 4.09μm and the maximum speed is 1741rpm, and the frequency is 58.05Hz. This kind of larger displacement will result in a certain degree of accuracy loss for precision edm.

Through the order analysis, we can draw the following conclusions:

1. The maximum order of vibration in the X direction is the first order and the two order, and the vibration of the two order is the most violent. The forced vibration at the first order shows that the forced vibration whose frequency is equal to that of the main shaft exists in the process of machine tool work. The main reason is that the dynamic balance of the bearing seat is not good. Forced oscillation at the two order is caused by the rotation of the motor, because the R shaft is driven by the motor through the belt which drive ratio is 2:1.

2. When the speed reaches 1400rpm, the vibration intensity begins to increase and when the speed reaches 1600rpm, the vibration is the most violent. Therefore, the speed higher than 1400rpm should be avoided in actual processing. This is also explained that the improvement of the structure, the structural rigidity of the X direction and the increase of the stable range of the speed can improve the production efficiency of the machine tool.

5. Conclusion

Through the above series of test and analysis, we can draw the following conclusions:

1. By analyzing the vibration modes obtained by modal testing, first of all, it is found that the dynamic stiffness of EDM machine tools is low, which is mainly caused by the second order modal of natural frequency 54.7Hz, which is exactly 3 times the frequency of 1000rpm. Secondly, it is found that the weak stiffness between the connecting plate and the bearing seat is the main reason for the low stiffness of machine tools. At the same time, through analysis of other main modal formation, it is found that the Q type stent is easy to produce Z direction vibration, and the joint surface of connecting plate and B axis also has the problem of unreliable connection. These are likely to restrict the improvement of the anti-vibration performance of the spindle of EDM machine tools.

2. By comparing the vibration modes of ODS test with the modal test, it can be found that in the two experiments the larger deformation structures are the union surface of the B axis and the connecting plate, the connecting plate and the Q type bracket, including the bearing seat. Therefore, the results of the two experiments are consistent, indicating that the experimental results are credible and reliable.

3. Through the order analysis, it is found that the vibration displacement of the machine tool in the X direction is relatively large. Therefore, it is necessary to strengthen the structural rigidity of the X direction and increase the stability interval of the speed, so as to improve the production efficiency of the machine tool. Specific measures include increasing the thickness of the board and designing stiffeners or dampers on the surface of the board.
Through a series of tests on EDM machine tools, the weak links of the machine tools are found, which provides a good reference for the structural optimization of machine tools.

Acknowledgements
This project is supported by 2018 Nova Program(Z181100006218078).

REFERENCE
[1] Wang Zhen-long, Zhao Wan-sheng. Micro EDM Technology in micro manufacturing system, 2003(9): 23-27.
[2] Cao Feng-guo. Special Processing Manual [M]. Beijing: China Machine Press, 2010.
[3] Chen Yun-xin, Wu Fu-ming, Deng Cheng-wen. Deliberated Wire Electrode Vibration Based on ANSYS [J]. Electromachining and Mould, 2006,(4), 26-28.
[4] Yang Da-yong. The development of EDM Technology [J]. Electromachining and Mould (Supplement), 2010:45-52.
[5] Yang Da-yong, Cao Feng-guo, Wang Shu-feng, et al. Development of multi axis precision CNC EDM machine [J]. Electromachining and Mould (Supplement), 2007:65-69.
[6] An Li-bao, Zhao Guo-guang. Spindle vibration test of EDM machine tool [J]. Aviation measurement technology, 1994 17-20