Research on Vibration Measurement System for Micro-milling Machine

Jia Zhenyuan, Wang Xinxin, Lu Xiaohong and Ren Zongjin

Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian, 116024, P. R. China.

(Received 17 August 2015; accepted 26 August 2016)

Micro milling is a machining technique. One of the challenges in micro milling is vibration, especially the relative vibration between the micro-milling cutter and workpiece, which influences the processing quality and tool life. Precise measurement of vibration is the precondition of vibration suppression. However, during the micro-milling process, cutting tools rotate at high speeds with feeding movements, and because the size of micro-milling machine is small and there’s limited space to install sensors. The situation above reveals the difficulty in acquisition vibration signal between cutting tool and workpiece. In this study, a laser displacement sensor holder able to realize the adjustment on multi degrees of freedom is designed, and a set of vibration measurement systems which utilizes laser displacement sensor to collect vibration signal during micro-milling process is developed. The research lays the foundation for vibration suppression of micro-milling, which can help improve surface quality and extend tool life.

1. INTRODUCTION

With the development of science and technology, high-accuracy miniaturized components and parts are increasingly needed. The development of micro components and parts shows a tendency of material diversification, structure complexity, and high dimensional accuracy, which makes for greater demands on micro-component and parts manufacturing techniques.1–5

Micro-milling technology developed quickly in recent years with many advantages such as being able to mill wide ranges of materials, high precision, lower energy consumption, lower equipment investment, high efficiency, and opportunities to fabricate 3D free-form surfaces.4–7 The dimension of parts machined by micro-milling is usually between 100 µm and 10 mm, and feature size is between 10 µm and 1 mm. The relative vibration between cutting tool and workpiece has great influence on quality and precision of micro-products during the processing.8

Figure 1 shows that chatter caused excessive burr in micro-milling Al 7075 workpiece.9 SEM images in Fig. 2 demonstrate the smooth and rough surfaces in micro-milling AISI 4340 steel workpiece in different dynamic conditions.8

Micro-milling tools with less than 1 mm diameter are easily worn and broken.10,11 Vibration causes wear and even breaking, which leads to higher costs and restrict applications of micro-milling technology.12–14 Therefore, vibration suppression during micro-milling is important to improve the quality and precision of micro-products, extend tool life, and reduce costs.15–17 Vibration measurement is the precondition of vibration suppression. In micro-milling, measurement of relative vibration between tool and workpiece is significant because relative vibration between tool and workpiece directly affects machining quality and tool life.

During the micro-milling process, cutting tools rotate at high speed with feeding movement, and there’s limited space to install sensors due to the compact size of micro-milling machines. Thus, it is difficult to measure the relative vibration signal between cutting tools and workpieces.18–20 Meaningful research on micro-milling vibration measurement have been done by scholars all around the world. Li Hongtao et al. adopted a three-axis accelerometer installed on the worktable to measure vibration signal, in order to study the vibration characteristics.21 Vibration suppression experiments were carried out by enhancing the damping and the stiffness of machine supporting component, which achieved some good results. However, the study was limited because the vibration signal collected was vibration in the machine tool body rather than relative vibration signal between tool and workpiece. Liu Zhibing et al. utilized a three-axis high impedance piezoelectric accelerometer to gather micro-milling vibration signal and study the distribution of vibration energy, the main frequency band of power spectrum, and energy dispersion degree.22 The results stated that the main frequency band of vibration signal is most sensitive to the change in feed direction of cutting the tool. Brock A. Mascardelli et al. used laser displacement sensor to measure micro-milling vibration.23 The laser displacement sensor was installed on the spindle and the laser spot was projected on the shank of cutting tool to monitor the vibration between cutting tool and spindle. Wan Hao Hsieh et al. developed a micro-tool monitoring system consisting of accelerometers and a backpropagation neural network, which actualized the tool wear prediction by using vibration signal.24 In the study, a three-axis accelerometer was installed on a sensor plate attached to the spindle housing to collect vibration signals in three directions during cutting. However, the information collected in the study is acceleration. If the reasonable upper and lower bound of integration is unknown, amplitude of vibration cannot be achieved.

In this paper, a vibration measurement system for micro-milling is developed. Vibration displacement signal is obtained by laser displacement sensor, a multi-degree adjustable holder for laser sensors is designed and manufactured, and a laser displacement sensor is installed in the holder to measure vibration in X, Y, Z directions. Data acquisition subsystem converts vi-
Vibration signal into digital data. Software developed with LABVIEW realizes the functions of data sampling, data analyses and displaying the frequency spectrum of vibration in real-time.

This paper comprises of five sections, the first two sections are focused on the measurement method and the laser sensor holder design. Followed by sections on measurement system design, hardware and software of the system is presented in detail. Environmental vibration suppression experiment and cutting vibration rules study are carried out with the measurement system.

2. PRINCIPLE OF MEASUREMENT

A laser displacement sensor is used to measure the vibration. As shown in Fig. 3, a laser displacement sensor is installed on the working table of micro-milling machine next to the designed laser sensor holder. The laser spot is emitted from the laser displacement sensor place on the spindle holder. In this paper, the workpiece, working table, holder for laser sensor and laser sensor are regarded as a rigid body. And the spindle holder and spindle are considered a rigid body. The sampled signal is actually the displacement between workpiece and tool cutter by substructure coupling, carried out in the stepping work. The sampled analogue signal will be translated to digital signal by data acquisition card installed in computer. The software developed in-house collects and analyses the digital data.
3. HOLDER FOR LASER DISPLACEMENT SENSOR

A multi-degree adjustable holder for laser displacement sensor is designed to measure vibration in X, Y, Z directions, as shown in Fig. 4.

The sensor holder is composed of horizontal baseboard, vertical baseboard, height adjusting plate, spherical joint and the sensor fixing plate. The horizontal baseboard can be fixed on working table of micro-milling machine in either X or Y direction. The vertical baseboard is fixed on the horizontal baseboard and the height adjusting plate is able to slide on the vertical baseboard to regulate the height of laser sensor. The sensor is fixed on the fixing plate which is connected with spherical joint. The spherical joint can rotate in all directions. Figure 5(a)–5(c) shows the installation of the holder on the machine table.

In Fig. 5(a), laser sensor is installed to measure the vibration in X direction. As the spindle holder locates in low height, a spherical joint is fixed to the horizontal baseboard directly without a vertical baseboard and height adjusting plate to ensure that the laser spot can play on the spindle holder.

To get the valid distance data, it’s necessary that the laser spot emitted from the laser displacement sensor must be projected onto the spindle holder, and that the distance between sensor and spindle holder should be around 25 mm. By moving the feeding table in Y direction, a laser spot can locate on the spindle holder. The distance between sensor and spindle holder can be adjusted by moving the feeding table in X direction.

In Fig. 5(b), a laser sensor is installed to measure the vibration in Y direction. Compared with Fig. 5(a), the horizontal baseboard holder rotates 90 degrees. By moving the feeding table in X direction, a laser spot can locate on the spindle holder. The distance between sensor and spindle holder can be adjusted by moving the feeding table in Y direction.

As shown in Fig. 5(c), a laser sensor is installed to measure the vibration in Z direction. A vertical baseboard and height adjusting plate are used to adjust the displacement sensor in a higher position, so that the laser spot can locate on spindle holder by moving feeding table in X and Y directions. The distance between sensor and spindle holder can be adjusted by adjusting the position of height adjusting plate relative to vertical baseboard.

The stiffness of the holder for laser displacement sensor is verified by finite element analysis. The maximum acceleration of the feeding platform is 0.68 g, and the total mass of laser displacement sensor and the sensor holder is 747 g. The maximum force applied on the holder is about 0.5 N. Using finite element analysis software, the displacement of holder for laser sensor can be calculated. The maximum deformation is 0.013 mm, which appears in the Sensor fixing plate in Z direction. This result shows that the deformation conditions of the structure can be ignored.

4. THE VIBRATION MEASUREMENT SYSTEM DESIGN

4.1. Hardware Design

The hardware of the vibration measurement system is mainly composed of a laser displacement sensor, laser controller, data acquisition card, and a computer (Fig. 6).

Distance information is obtained by the laser displacement sensor and is converted into analogue voltage signals by the laser controller. The analogue voltage signals are linearly related to the distance. The analogue voltage signals are converted into digital signals by data acquisition card and sent to the computer using a high-speed data bus for collection, reservation, and analyses.

The Microtrak II LTC-025-02 laser displacement sensor produced by MTI Instruments Corporation is used. The specifications are as follows: laser wavelength is 670 nm; power of laser is 2–5 mW; standoff distance is 25 mm; the measurement range is ±1 mm; the resolution is ±0.12 µm; the linearity is 0.05 %; and the response frequency is 20 KHz. The laser displacement sensor is connected to laser controller. Analogue voltage signals linearly related to distance are generated by laser controller. The PXI-4462 high-accuracy data acquisition card produced by National Instrument Corporation is adopted in order to simultaneously sample four analogue voltage inputs. The maximum sampling rate is up to 204.8 KS, and the minimum voltage resolution is 37.3 nV. PXI-4462 data acquisition card is installed to a PC-based PXI computer. The PXI computer has many advantages such as high reliability, good extensibility, high data bandwidth, and a strong processing capacity.

4.2. Software Design

The software is developed with LABVIEW. The functions of the system software are mainly composed of parameter setting, data recording, data analysis, data playback and help.

Figure 4. Structural of multi-degree adjustable holder for laser displacement sensor.
The function and structure diagram of the measurement system software is shown in Fig. 7.

The sampling parameters for the data acquisition card can be set in the module of parameter setting, such as channel number, signal coupling mode, sampling rate, buffer size, type of window function for frequency spectrum, times of average, and data storage path for frequency domain and time domain.

The constitution of vibration signal can be identified after converting the time domain vibration wave into frequency domain. The module of data analysis function in the software converts the time domain vibration data into frequency domain data and display the wave of data in real time. The module of data recording is used to save both the time domain vibration data and the frequency domain vibration data. Vibration waves can be reconstructed after experiment by data playback module. There is also cursor read function to show the amplitude of vibration at each point in real time.

5. EXPERIMENT STUDY

To verify the usefulness of the developed measurement system, environmental vibration experiment and micro-milling vibration rules experiment are carried out on our micro-milling machine. The environmental vibration experiment serves mainly to analyse the influence of external devices and verifying the inhibiting effects of precise air-cushion isolation platform. The cutting vibration rules experiment is to study the vibration rules during the micro-milling processing of nickel-based superalloy Iconel718.

5.1. Micro-Milling Machine Test Bench

The research is based on the self-developed three-axis micro-milling machine shown in Fig. 8. The body size of the machine is $194 \text{ mm}(X) \times 194 \text{ mm}(Y) \times 400 \text{ mm}(Z)$, the workspace size is $50 \text{ mm}(X) \times 50 \text{ mm}(Y) \times 102 \text{ mm}(Z)$. The feed system in $X, Y, Z$ directions uses servo motor to drive precise ball screw and equips with linear encoders. The absolute position accuracy of the axes $X, Y, Z$ is 1 $\mu$m and repeat position accuracy is 0.2 $\mu$m. The high-speed electric spindle produced by IBAG Company rotates from 40000 rpm to 140000 rpm and the radial run-out tolerance of the spindle is less than 0.2 $\mu$m.
The selected cutting tools are ultrafine particle coated cemented carbide end milling tools with 2 flutes whose diameter is 0.2 mm made by UNION TOOL Co., as shown in Fig. 9. The parameters of the end milling tools are shown in Table 1.

5.2. Environmental Vibration Experiment

The influences of potential vibration sources such as the cooled-air compressor, lubricant pump, and cooling pump for the spindle are checked through the environmental vibration experiment. In this experiment, the CNC-machine is shut down, with no feeding or milling. By comparing the vibration before and after turning the potential vibration source on, vibration influences from external device on the machine can be estimated.

The results are listed in Tables 2–4. The peak amplitude between workpiece and spindle in X, Y, Z directions is around 46 Hz. Asynchronous motors are used in these devices. The rated rotation speed of asynchronous motor is shown as:

\[ n_N = \frac{60 f_N}{P}; \]  

where \( n_N \) is the rated rotation speed (rpm), \( f_N \) is the rated frequency of power supply (Hz), and \( P \) is the poles number of the asynchronous motor.

In the experiment, frequency of power supply is \( f_N=50 \) Hz, the poles number of the asynchronous motor is \( P=2 \), thus \( n_N=1500 \) rpm, and the rated rotation speed of asynchronous motor is \( 25 \text{ R/s} \). The actual rotation speed of asynchronous motor is shown as:

\[ n = S \times n_N; \]  

where \( n \) represents actual rotation speed, and \( S \) represents slip ratio \((0 < S < 1)\). The actual rotation speed of motor is always less than the rated rotation speed.

There are pistons driven by the asynchronous motor in cooled-air compressor, lubricant pump, and cooling pump for the spindle. The asynchronous motor drives pistons into a reciprocating motion; when asynchronous motor rotate one revolution, piston move alternately once and vibration occurs twice. Therefore, vibration frequency is double the rotation frequency of motor. In the experiment, the rated rotational frequency of motor is 25 Hz, larger than actual rotational frequency. Thus, the frequency of the vibration excited by the reciprocating motion of piston should be less than 50 Hz. In the experiment, the peak amplitude of vibration appears at 46 Hz, which is consistent with the theory.

The amplitude of vibration in X direction excited by external devices at 46 Hz is 0.0945 \( \mu \text{m} \), and peaks appear at two times, three times and four times of the fundamental frequency. In Y direction, the vibration amplitude is 0.1565 \( \mu \text{m} \) at 46 Hz and at two times of the fundamental frequency there exists peak. In Z direction, the vibration amplitude is 0.1457 \( \mu \text{m} \) at 46 Hz. The vibration amplitudes excited by external devices in Y and Z direction are almost the same, and are larger in X direction. However, the frequency distribution of vibration signal in X direction is broader than the other two directions.

The micro-milling machine is placed on the passive precise air-cushion vibration isolation platform. The isolation function of the platform can be deactivated by cutting off the air supply. The practical vibration isolation effect of the platform can be judged through the contrast experiment.

Tables 2–4 show the isolation effect of the precise air-cushion vibration isolation platform. Vibration over 3 Hz is reduced obviously, but there is no significant vibration isolation effect at 3 Hz or less. As the natural frequency of the precise air-cushion vibration isolation is 3 Hz, air-cushion isolation has no effect on the vibration at the frequency lower than the natural frequency.

5.3. Cutting Vibration Rules Study

Utilizing the self-developed vibration measurement system, vibration in actual micro-milling process is tested. The work-
frequency derived by the rotary part is calculated through $f = \frac{n}{60}$ Hz, which is about 1166 Hz. As the adopted cutting tool is two-flute, cutting occurs twice when the spindle rotates one revolution. While vibration occurs at 1160 Hz, it states that the phenomenon of single-tooth cutting exists during the process. Vibration is mainly closely related to spindle speed, and there’s phenomenon of single-tooth cutting during the process. Vibration is mainly distributed at the first order and second order of the vibration frequency derived by the spindle.

The developed vibration measurement system for micro-milling machine offers an effective test method for the research of major factors and influence rules of vibration during micro-milling. The research lays the foundation for vibration suppression of micro-milling, which can help improve surface quality and extend tool life. At present, vibration can only be measured in one direction at one time. The system can be extended to measure vibration in three directions at the same time in future.

6. CONCLUSIONS

A set of vibration measurement system for micro-milling is developed, which utilizes laser displacement sensor to collect vibration signal during micro-milling process. In order to resolve the difficulty in installation of laser displacement sensor for the measurement of relative vibration, a new kind of multi-degree-adjustable holder is developed for laser displacement sensor. An environmental vibration experiment and a micro-milling vibration rules experiment are carried out on the micro-milling machine developed in-house. It is found that the workpiece material is nickel-based superalloy Inconel718. The slotting experiment is carried out using micro-milling tool with 2 flutes whose diameter is 0.2 mm. Spindle rotational speed is 70000 rpm, feeding rate is 1 mm, axial depth of cutting is 40 $\mu$m. The results are shown in Fig. 10.

There are peak amplitudes at 1160 Hz in $X, Y, Z$ directions, as the rotation speed of the spindle is 70000 rpm, the vibration frequency derived by the rotary part is calculated through $f = \frac{n}{60}$ Hz, which is about 1166 Hz. As the adopted cutting tool is two-flute, cutting occurs twice when the spindle rotates one revolution. While vibration occurs at 1160 Hz, it states that the phenomenon of single-tooth cutting exists during the micro-milling process. There are peak amplitudes in all of $X, Y, Z$ directions at 2330 Hz. The vibration frequency is twice the spindle rotation frequency, which meets the calculating result well. The peak amplitudes of $Y$ direction is the largest, $Z$ direction is the second largest, and $X$ direction is the smallest.

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 under project number: 20120041120034; and the Fundamental Research Funds for the Central Universities under project number: DUT13LAB13. The financial contributions are gratefully acknowledged.

REFERENCES

https://dx.doi.org/10.1016/j.jmachtools.2005.05.015

https://dx.doi.org/10.1115/1.1813469

https://dx.doi.org/10.1016/S0007-8506(07)62071-X

https://dx.doi.org/10.1016/j.measurement.2013.02.002


https://dx.doi.org/10.1016/j.cirp.2012.03.012


https://dx.doi.org/10.1016/j.jmatprotec.2009.06.009

https://dx.doi.org/10.4028/www.scientific.net/AMM.217-219.1791

https://dx.doi.org/10.1007/s00170-005-0276-6

https://dx.doi.org/10.1016/j.ijmachtools.2011.12.010

https://dx.doi.org/10.1108/ILT-07-2015-0114

https://dx.doi.org/10.1504/IJSURFSE.2014.060484

https://dx.doi.org/10.1016/j.wear.2012.08.011

https://dx.doi.org/10.1007/s10853-006-0171-z

https://dx.doi.org/10.1007/s00170-010-2856-3

https://dx.doi.org/10.1016/j.ymssp.2012.07.006

https://dx.doi.org/10.4028/www.scientific.net/AMM.217-219.2187

https://dx.doi.org/10.1007/s00170-009-2213-6

https://dx.doi.org/10.1504/IJNMM.2009.027049


https://dx.doi.org/10.1115/1.2816104

https://dx.doi.org/10.1007/s00170-011-3703-x