Evaluation Method and Experimental Study on Stationarity of High-Precision Linear Motion

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Abstract: In this paper, a method for detecting the high-precision linear motion stability of CNC machine tools is proposed, and the four indexes of maximum fluctuation, rate accuracy, rate stability and rate volatility are used as the evaluation indexes of linear motion stability. Based on the principle of laser interferometry, this method uses Quick View XL™ from Renishaw to collect machine operating data for linear motion stability analysis. The experimental results show that the evaluation method can effectively quantify the key indicators of linear motion stability performance.

1. Introduction
Accurate and stable feed rate is one of the important factors influencing the metal removal rate and surface finish. Especially in the field of ultra-precision machining, the stability of linear motion is particularly important. At present, a lot of research has been carried out at home and abroad on the speed stability of machinery such as turntables and robots. Among them, scholars from Harbin Institute of Technology [1] and Xi'an University of Electronic Science and Technology [2] have conducted a series of research on the speed stability of turntables. Shen J [3], Chwastek S [4] and Hui L [5] et al analyzed the control method of the speed stability of the turntable and feed system. Besides, Yuan J [6] and Choi P J [7] et al studied the motion stability of the robot arm. In theoretical research, Fuller A T et al [8] systematically analyzed the stability of motion. However, for the smoothness of the linear axis, the low-speed inhomogeneity is mainly analyzed [9,10], and little research has been done on the high-precision linear motion stability evaluation.

On this basis, this paper proposes a method for detecting the high-precision linear motion stability of CNC machine tools, and uses four indicators as the characterization of the linear motion stability. Based on the principle of laser interferometry, the method collects the data of machine for analysis and calculation, and obtains the quantitative evaluation results of the key indicators of linear motion stability.

2. Evaluation Index
In order to evaluate the smoothness of linear motion, the evaluation index should be first proposed. Through theoretical analysis, four key indicators are proposed and the accuracy and fluctuation of the motion are comprehensively analyzed.

2.1 Maximum fluctuation
This indicator intuitively reflects the maximum fluctuation of motion. The formula for the calculation is as follows:

\[
\Delta v = v_{\text{max}} - v_{\text{min}} \tag{1}
\]

Where: \(v_{\text{max}}\) is the maximum speed; \(v_{\text{min}}\) is the minimum speed; \(\Delta v\) is the maximum fluctuation.

2.2 Rate accuracy

Rate accuracy refers to the accuracy of the actual rate, indicating the consistency of the actual velocity of the linear motion with the theoretical value. Calculated as follows:

\[
v_j = \frac{1}{v_g} \left| \overline{v} - v_g \right| \tag{2}
\]

Where: \(v_g\) is the nominal value (theoretical value) of a given rate; \(\overline{v}\) is the average (actual value) of the speed of multiple measurements; \(v_j\) is the rate accuracy.

At present, the speed measurement method includes two methods, a method of measuring distance at fixed time and a method of measuring time at fixed distance.

2.2.1 Method of measuring distance at fixed time

The machine operates in rate mode at a given rate. When it is stable, the linear axis position increment is read at a time interval \(t\). Based on the speed calculation formula, the displacement increment divided by the time interval \(t\) is the machine speed. It should be noted that the selection of the fixed time interval \(t\) is related to the given rate command. The mathematical expression of the rate accuracy of the timing ranging method is as follows:

\[
v_j = \frac{1}{v_g} \left| \overline{L} - L_g \right| \tag{3}
\]

Where: \(L_g\) is the nominal value (theoretical value) of the position increment for the linear axis at a given rate and given time interval. \(\overline{L}\) is the average (actual value) of the position increment for multiple measurements.

2.2.2 Method of measuring time at fixed distance

The linear axis operates in the rate mode according to the given rate. The fixed position interval \(l\) is selected. After the stable operation, the time taken for the linear motion to travel through the fixed position interval is measured, and the measurement is performed multiple times. The mathematical expression of the rate accuracy of the distance measuring method is as follows:

\[
v_j = \frac{1}{v_g} \left| \overline{T} - T_g \right| \tag{4}
\]

Where: \(T_g\) is the nominal value (theoretical value) of the time taken by the linear axis at a given rate and a given position interval. \(\overline{T}\) is the average of the time increments of multiple measurements (actual value).

2.3 Rate stability

Rate stability refers to the smoothness of speed, in other words, the deviation of speed from its average value. The formula is as follows.
Where: $N$ is the number of measurements; $v_i$ is the speed of the $i$th measurement; $\bar{v}$ is the average of the multiple measurements; and $v_o$ is the rate stability factor.

Tip 1: The choice of the number of measurements $N$ is related to the given rate. In fact, the rate stability is the mean square error of the rate accuracy, which is the average of the distances of the data from the mean. It is used to estimate the fluctuation degree of the actual rate around the mean and quantitatively evaluate the overall volatility of the speed.

In the same way, the rate stability calculation methods of the two methods of timing ranging and distance measurement are analyzed.

### 2.3.1 Method of measuring distance at fixed time

The formula for calculating the Rate stability of the timing ranging method is as follows.

$$v_o = \frac{1}{\sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (v_i - \bar{v})^2}}$$

$$= \frac{t}{L} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{L_i}{t} - \bar{L} \right)^2}$$

$$= \frac{1}{L} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (L_i - \bar{L})^2}$$

Where: $N$ is the number of measurements; $L_i$ is the position increment of the $i$th measurement; $\bar{L}$ is the average of the position increments of multiple measurements.

### 2.3.2 Method of measuring time at fixed distance

The formula for calculating the rate stability of the fixed distance measuring method is as follows.

$$v_o = \frac{1}{\sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (v_i - \bar{v})^2}}$$

$$= \frac{\bar{T}}{T} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{T_i}{\bar{T}} - 1 \right)^2}$$

$$= \frac{1}{\bar{T}} \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (T_i - \bar{T})^2}$$

Where: $N$ is the number of measurements; $T_i$ is the time interval of the $i$th measurement; $\bar{T}$ is the average of the time intervals of multiple measurements.

### 2.4 Rate volatility

Rate volatility reflects the fluctuation of motion from another angle. The definition of it is as follows.

$$v_o = \frac{\Delta v}{\bar{v}} \times 100\%$$

Where: $\Delta v$ is the maximum fluctuation of the rate, $\bar{v}$ is the average speed. If the value of $v_o$ is smaller, the velocity fluctuation of linear motion is smaller, and the machine tool runs more smoothly,
on the contrary, the operation is more unstable. The initial setting is $v_0 < 0.2$. In principle, it can be considered that the running smoothness is better.

3. Detection method

3.1 Measurement principle
In this paper, the velocity of linear motion is measured based on the principle of laser interferometry. Interferometry is a technology of incremental method based on the principle of light wave interference. It fixedly connects the reflector and the test object; the interferometer mirror is fixed. When the reflector moves with the test object, the difference of the optical path between two beams will change, and the interference fringes will alternate alternately. Finally, the measured distance can be determined by detecting the number of interference fringes in the photoelectric detector. Further, within a specified time interval, the movement distance in that time interval is obtained. On paper, the average value of the moving distance is the average velocity of the object. When the time interval is small enough, it can be approximately considered as instantaneous velocity.

3.2 Test
According to GB/T17421.1, environmental conditions, temperature rise and other test conditions were pretreated. And a standard program is compiled to make the moving parts move along a straight line for a period of time (for example, 5 seconds) and record the actual speed, which is generally a velocity fluctuation curve with burrs.

3.2.1 Test subjects
The Y-axis motion stability of a gantry machining center is tested, the full stroke is 2000mm, and the cutting speed range is (1~7000)mm/min.

3.2.2 Test Instruments
The measurement is performed by the Quick View XL™ provided by Renishaw XL-80). The sampling frequency is 10Hz~50kHz, the speed range is (0~4)m/s and the accuracy is ±0.04%, which meets the requirement of measurement accuracy. Before the test, the pre-trigger time, post-trigger time, and sampling frequency need to be set. The measuring device is as follows:
- Quick View XL™ software;
- A Renishaw XL80 laser head;
- A Renishaw XC environmental compensation unit;
- A set of measuring optics, including spectroscopes, mirrors and related mounting components;
- A notebook or desktop PC.
The installation of the equipment is shown in Figure 1.

4. Results
(1) Test 1: Stationarity of linear motion at different sampling frequencies
The choice of sampling frequency (how many sample points per second) will affect the quality of the test results.
Sampling time is set to 2 seconds, and the detection area is in the middle of the Y axis. The same velocity wave is sampled at different sampling frequencies for data acquisition and stationarity
evaluation. When the set speeds are 100mm/min and 1000mm/min respectively, the curve of stationarity of linear motion with sampling frequency is shown in figs. 2 and 3.

Figure 2. The curve of the stationarity of motion with the sampling frequency when the speed is 100mm/min.

Figure 3. The curve of the stationarity of motion with the sampling frequency when the speed is 1000mm/min.

(2) Test 2: Stationarity of linear motion at different set speeds
Exploring the variation of the linearity of linear motion at different set speeds, the detection parameters are set as follows: sampling time is 2s; the measurement area is the middle of the Y axis; sampling frequency is 50kHz. Figure 4 is the curve of the stationarity of motion with the setting speed.

Figure 4. The curve of motion stationarity varying with speed.

(3) Test 3: Stationarity of linear motion of linear axes at different mechanical positions
The detection parameters are set as follows, the sampling time is 2s, the detection position is in the middle of the Y axis, sampling frequency is 50 kHz and the set speed is 100 mm/min.
Figure 5. The curve of motion stationarity varying with the detection area

(4) Test 4: Stationarity of linear motion at different sampling times
The detection area is in the middle of the Y axis, the sampling frequency is 50 kHz, and the speed is 100 mm/min. The measurement time range is determined by the maximum feed rate and the full stroke of the linear axis. It should be noted that the acceleration/deceleration section should be avoided during the measurement, and the measurement is started after the machine runs smoothly.

Figure 6. The curve of motion stationarity varying with the sampling time

(5) Test 5: Stationarity of linear motion under different filter time constants
The detection parameters are set as follows: sampling time is 2 s, detection area is in the middle of Y axis, sampling frequency is 50 kHz and setting speed is 100 mm/min.

Figure 7. The curve of motion stationarity varying with the filter time constants

5. Discussion
Based on the results, the following conclusions can be drawn:
(1) Test 1, with the increase of sampling frequency, the values of each evaluation index are gradually stable. In figures 2 and figures 3. When the sampling frequency is greater than a certain value, the indicators are basically unchanged. According to the sampling theorem, the lowest sampling frequency must be twice the signal frequency. If a sampling frequency is given, the maximum frequency at which the signal can be correctly displayed without distortion is called the Nyquist frequency. If the signal contains a component with a frequency higher than the Nyquist frequency, the signal will be distorted. The test results are consistent with the theory. The test show that it is recommended to set the sampling frequency to 5~10 times of the highest frequency of the signal. An empirical value 1kHz of sampling frequency is also given.

(2) Test 2, as the speed increases, the value of maximum fluctuation and rate stability increases, and rate volatility and rate accuracy decrease, which is consistent with the actual situation. In fact, when the speed increases, the greater the fluctuation of machine tools;

(3) Test 3, the linear axis has different detection area. The closer to the tail, the maximum speed fluctuation is obviously increased, and other parameters are relatively stable. It is related to the structure of the machine tool itself. The front end of machine tool is commonly used in processing area, and its motion stability is also high.;

(4) Test 4, the longer the sampling time, the larger the maximum fluctuation of the rate is, the trend of the rate fluctuation rate is relatively flat, and the other parameters are relatively stable. Theoretically, the longer the sampling time, the greater the probability of large fluctuations, which is consistent with the actual situation.

(5) Test 5, with the increase of filtering time, the maximum fluctuation, rate stability and rate volatility all show a downward trend, and the rate precision value is relatively stable. The exponential filtering function can be used to reduce the noise caused by electrical noise and vibration or air disturbances. It should be reasonably set to avoid losing valid information. It is recommended to set it up to 63% of the time required for the laser readout change after a step move.

6. Conclusions
Based on the principle of laser interference, a method for detecting the stationarity of linear motion is proposed in this paper. Combined with the experiment, the parameters such as sampling frequency, sampling time, filtering time and motion speed which affect the validity of the detection results are studied. And the stationarity of linear motion is evaluated by four indexes: maximum fluctuation, rate accuracy, rate stability and rate volatility. The experimental results are consistent with the actual situation, which indicates that the detection and evaluation method proposed in this paper can effectively quantify the stationarity of linear motion.

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