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Novel method for detection of anomalous structure characteristics of ID precision ultrathin monocrystalline silicon section cutting tool*

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Abstract： The structure characteristics of ID precision ultrathin monocrystalline silicon section cutting machine-tool spindle with force-monitoring bearings functioning as force measuring sensors were detected with the new Hilbert theory based signal-wave envelope detection method，presented to replace the conventional hardware device in order to ensure that the signal is measured online with high fidelity. According to the probability of anomalous incidents in the cutting process，a mathematical recognition model has been designed and verified on an STC-22ID machine.

Key words： Machine-tool spindle，Bearing，Monocrystalline silicon section，Signal analysis
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INTRODUCTION

As circuits integrated more intensively and silicon section more extensively，the silicon section manufacturing precision and smoothness are more rigorously required，especially for crystal lattice integrity. Therefore，online monitoring of three-dimension cutting force and tool breakage becomes more important in the machine-tool spindle system of ID machine（Inner Diameter precision ultrathin monocrystalline silicon section cutting machine）. In the USA，Switzerland，and other technologically developed countries，the cutting process monitoring has been computerized，especially for automatic cutting process and tool deviation，but not yet for online monitoring of cutting force and tool breakage（Wang，1993）. In general，the monitoring system performance depends mostly on the sensors' characteristics（Bahr et al.，1997）. A variety of spindle sensors of cutting force or torque，tool wear and breakage，machine power，etc.，and coordinated equipment，had been applied in respective areas（Kegg，1993；Liu et al.，2000；Novak et al.，1996；Nair et al.，1992）. The ID machine spindle structure is special in that its force-monitoring bearings also serve as spindle bearings. The force-monitoring bearing not only functions as a bearing of the spindle but also measures the static and dynamic cutting force of the spindle（Guo，1993）.

In the 1990s，Swedish SKF Co. was able to use conventional products for force-monitoring bearings and developed corresponding apparatus. The applied force-monitoring bearing manufactured by German FAG Co. can measure cutting force as well as spindle pre-load so as to determine actual bearing working condition，then adjust the lubricant supply amount（Glockner，1985）. The theory and application of force-monitoring bearings had also been researched for years in Zhejiang University（Chen，1992）. However，in the collection and processing of the force-

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monitoring bearing's signals, the usually applied signal-wave envelope demodulation circuit performs poorly when the dynamic force frequency exceeds the carrier frequency or the carrier frequency frequently varies. This paper presents a new design and signal processing method to monitor online the three-dimension cutting force and tool breakage in the ID machine spindle system. In addition, renovation of the American STC-22 ID machine enabled detection of the anomalous working condition of the ID precision ultrathin monocrystalline silicon section cutting machine.

STRUCTURE OF FORCE-MONITORING BEARING

In this work, the force-monitoring bearing was adapted from the original STC-22 ID machine spindle bearing 7112AC. The installation size was the same as that of the original; in addition, the strain gauge and its wires are inserted in a groove ground in the outer ring periphery and at the roller-and-outer-ring contact load axial direction (Fig. 1). As the bearing rotates, a DC bridge transforms the variation of strain gauge resistance to voltage variation proportional to the bearing load after calibration.

Fig. 1 shows four pairs of strain gauges named 1-1′($R_1 - R_{1'}$), 2-2′($R_2 - R_{2'}$), 3-3′ ($R_3 - R_{3'}$) and 4-4′($R_4 - R_{4'}$), comprising four D. C. bridges. The load signals were measured as follows.

$$F_1 \propto F_X + F_a + F_V$$
$$F_2 \propto F_Y + F_a + F_V$$
$$F_3 \propto -F_X + F_a + F_V$$
$$F_4 \propto -F_Y + F_a + F_V$$

where

$F_V =$ centrifugal load,

$F_a =$ axial load,

$F_X =$ X-axis direction radial load,

$F_Y =$ Y-axis direction radial load,

F_1, F_2, F_3, $F_4 =$ respective measured load by using four pairs of strain gauges 1-1′, 2-2′, 3-3′ and 4-4′.

The spindle load at actual working condition can be determined through simple addition and subtraction among the four group's signal.

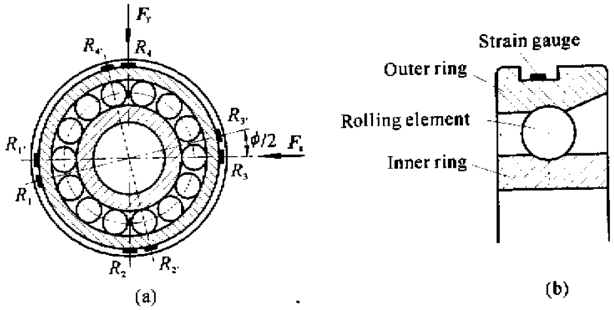

Fig. 1 A force-monitoring bearing diagram
(a) gauge distribution; (b) structure

ANALYSIS OF FORCE-MONITORING BEARING OUTPUT SIGNAL

Fig. 2 shows the output signal of a specific strain gauge bridge. The signal waveform has the characteristics of a modulated signal.

$$X(t) = F(t) \cdot Y(t)$$

where

$F(t)$ = modulated signal containing bearing load;

$Y(t)$ = carrier with frequency f_n as follows:

$$f_n = \frac{z \cdot n}{2 \times 60} \cdot \left(1 - \frac{d_k}{d + D} \cdot \cos\alpha\right)$$

where

d = bearing bore diameter(mm);

D = bearing outside diameter(mm);
d_k = rolling element diameter(mm);
Z = number of rolling elements;
α = contact angle(degrees);
n = spindle speed(r/min).

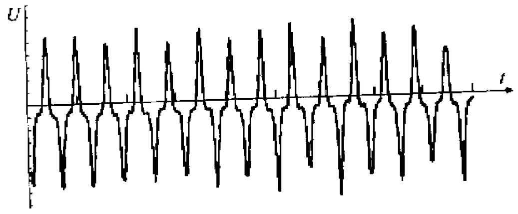

Fig. 2 Measured signal from a detection circuit bridge

Hence, the carrier measured from the force-monitoring bearing is proportional to the spindle speed and the number of rolling elements, whereas the signal amplitude reflects the bearing load. A key objective is the effective picking up of the modulated signal amplitude.

COLLECTING THE MODULATED SIGNAL AMPLITUDE OF FORCE-MONITORING BEARINGS

1. Envelope detection

Fig. 3 shows a series envelope detection circuit and its output signal-wave with ripples imposed on it. The output is largely influenced by RC. A larger RC can distort the output signal, whereas smaller RC can also decrease the mean voltage of the output signal and increase the ripple voltage as well. As a consequence, this kind of detection circuit can't be applied well for measuring the dynamic force which has been rapidly varying frequency.

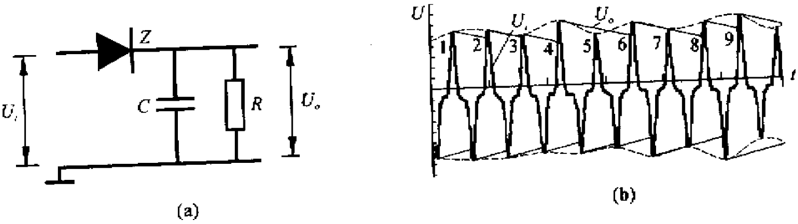

Fig. 3 A series envelope detection circuit
(a) principle of detection circuit; (b) output signal-wave

2. Hilbert transforming detection

In order to improve measuring precision, Hilbert transformation was adopted to ensure that the signal collected from the force-monitoring bearing is of high enough fidelity to reflect the transient load. The Hilbert algorithm principle is expressed as follows,

$$\widetilde{X}(t) = H\{X(t)\} = \int_{-\infty}^{\infty} X(\tau)\frac{1}{\pi(t-\tau)}\mathrm{d}\tau$$

$X(t)$ serves as the real part and its Hilbert transformation $\widetilde{X}(t)$ is the imaginary part of the function,

$$\hat{X}(t) = X(t) + j\widetilde{X}(t) = |\hat{X}(t)|\mathrm{e}^{j\theta(t)}$$

where

$|\hat{X}(t)| = \sqrt{X^2(t) + \widetilde{X}^2(t)}$, frequency-amplitude characteristic of $\hat{X}(t)$;

$\theta(t) = \tan^{-1}\frac{\widetilde{X}(t)}{X(t)}$, frequency-phase characteristic of $\hat{X}(t)$.

Shun (1991) proved that $|\hat{X}(t)|$ is the envelope function of $X(t)$, so the original signal can be demodulated through $|\hat{X}(t)|$.

As a matter of fact, Hilbert transformation is a convolution by $x(t)$ and $h(t)$, namely $X(t)\cdot h(t)$. During the period T_0, the output signal from a force-monitoring bearing is comprised of a series of discrete signals x_1, x_2, ... x_n separated by a sampling interval Δt.

When $t = k\Delta t$, the discrete convolution algorithm can be used to obtain the discrete Hilbert transformation as:

$$\widetilde{X}(t) = \frac{1}{\pi}\sum_{i=1}^{n} X(i\Delta t) \cdot \frac{1}{k-i}$$
$$k = 1, 2, K, n$$

Then, the discrete amplitude, i. e. the discrete envelope function is as follows,

$$Y_k = \sqrt{X_k^2 + \widetilde{X}_k^2} \qquad k = 1, 2, K, n$$

When $n = 100$, i. e. a cycle T_0 is divided into $100\Delta t$, the above-mentioned calculation precision is 1%.

MATHEMATICAL MODEL OF TOOL ANOMALOUS WORKING CONDITION

The characteristic parameter determination for a spindle monitoring system is related to a specific cutting mode. In the process of monocrystalline silicon section cutting, the cutting force is resolved into a tangent cutting-force F_t, a perpendicular cutting-force F_n and an axial cutting-force F_a. It was proved that F_n is about 4 times F_t and that F_a is relatively smaller; so F_t and F_n can serve as monitoring parameters. Then, after designing related mathematical models and recognition algorithms, F_t and F_n can be used to monitor online tool wear and breakage.

It is known from experience that the cutting force of a new tool gradually comes to a stable status after tentatively cutting $n_0 (< 20)$ silicon chips. Then, the cutting force varies less within $n_s (< 200)$ silicon chips. When the number of chips exceeds 200, the tool starts to be intensively worn. As the number of chips n_w reaches 300, the cutting force of the blunt tool is apparently increased with the sharp decrease of cutting precision, in addition, it is possible to cause tool breakage, or "explosion". Accordingly, to prevent a tool from excessive wear and breakage, an algorithm for anomalous tool condition detection is designed as follows:

1. Determine datum registers

For chips number of sampling points $N = n_0$, the datum cutting forces F_{tb} and F_{nb} are

$$F_{tb} = \frac{1}{N}\sum_{i=1}^{N} F_{ti}$$
$$F_{nb} = \frac{1}{N}\sum_{i=1}^{N} F_{ni}$$

where

F_{tb}, F_{nb} = transient sampling forces when $N = n_0$.

2. Determine transient mean forces within a specific period

When N is located in the zone (n_0, n_s), the online transient average cutting forces are

$$F_t = \frac{1}{N}\sum_{i=1}^{N} F_{ti}$$
$$F_n = \frac{1}{N}\sum_{i=1}^{N} F_{ni} \qquad (N \in [n_0, n_s])$$

3. Determine overall force ratios

The overall force ratios are applied to determine online tool wearing status.

$$\mu_t = F_t / F_{tb}$$
$$\mu_n = F_n / F_{nb}$$

where

F_t, F_n, F_{tb}, F_{nb} = maximum average force among respective force spectrums.

4. Overall ratios distinguishing formulas

For overall ratios μ_{tw} and μ_{nw}, the distinguishing formulas for tool breakage are

$$\mu_t > \mu_{tw}$$
$$\mu_n > \mu_{nw}$$

The thresholds μ_{tw} and μ_{nw} are related to the tool performance, and provided by the tool database.

TOOL ANOMALOUS STATUS DETECTION

The tool anomalous condition includes two anomalous phenomena, i. e. tool wear and tool anomalous installation, which lead to cutting excessive increment.

When the experience database has not been constructed completely, the relevant thresholds are determined through a self-learning process. In the overall ratios distinguishing process, the perpendicular force F_n or μ_n is defined as recognition parameter. Fig. 4 shows the test result showing the correlation between μ_n and the number of the chip (n). In Fig. 4, when n varies from n_0 to n_w, μ_n varies from 1 to 2.4, i. e. 2.4

times the initial state; so the threshold μ_{nw} of μ_n is defined as 2.4 (n is about 300) and the threshold of the tangent force F_t can be defined in the same way. Meanwhile, the measured axial force (F_a) is the axial cutting force, which can be used to determine the tool wear so that the curved chip can be inferred. In the end, the algorithm has been verified to be capable of preventing excessive tool wear and breakage resulting from serious accidents in the STC-22 ID machine in the National High-purity Silicon & Silicane Key Lab.

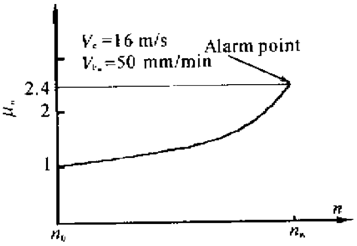

Fig.4 n vs. μ_n

V_c, tangent speed; V_{F_n}, perpendicular cutting speed

CONCLUSIONS

With the force-monitoring bearings functioning as force-measuring sensors in the spindle of the ID precision ultrathin monocrystalline silicon section cutting machine, it is possible, with the use of Hilbert transform theory, to construct the mathematical model and detect the anomalous working condition. This model can replace the conventional envelope detection circuit method. Some conclusions are as follows.

1. As a new sensor, the force-monitoring bearing can measure three-dimensional load in the ID machine-tool spindle.

2. When the speed of the ID machine-tool spindle reached 2000 r/min, the carrier frequency collected through the B46112 force-monitoring bearing was 467 Hz. The conventional envelope detection circuit can't process the dynamic load signal with > 467Hz frequency, but the new method presented in this paper can process the dynamic load signal with frequency as high as the strain gauge upper cut-off frequency.

3. With the Hilbert transformation based signal envelop detection method replacing the conventional envelope detection circuits, the signal can be measured with high-fidelity on line.

4. The new mathematical model of tool anomalous working condition and the algorithm for cutting process monitoring are simple and practical, and can be applied to effectively prevent tool excessive wear and breakage.

Finally, the new method has been successfully tested in STC-22 ID machine and can serve as an effective tool for scientific research work on the ultrathin monocrystalline silicon section cutting-process mechanism.

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