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Tool Condition Monitoring based on Vibration Signal from an On-Rotor Sensor in CNC Turning Process

Chun Li, Dongqin Li, Dawei Shi, Guojin Feng, Bing Li , Hongjun Wang , Fengshou Gu , Andrew D Ball

Centre for Efficiency and Performance Engineering (CEPE)
School of Computing & Engineering,University of Huddersfield, Huddersfield, UK
School of Industrial Automation,Beijing Institute of Technology, Zhuhai, China

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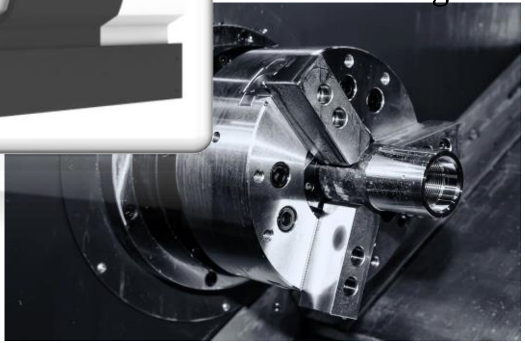
Outline

1. Introduction


Turning


Face cutting

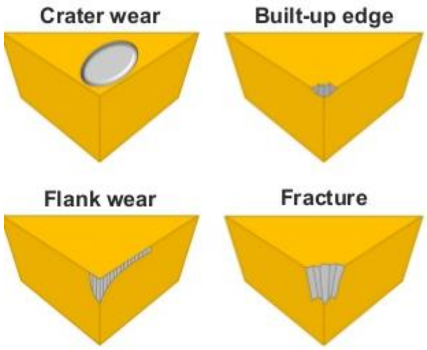

Drill

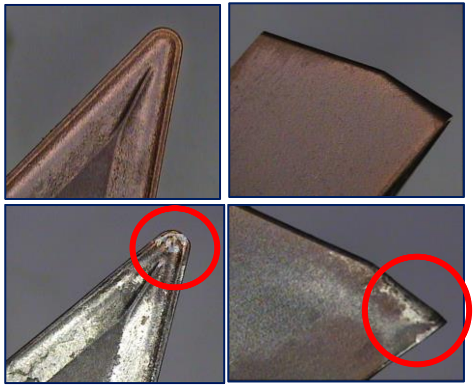

Finish hole

In mechanical processing, 70-80% of the parts are formed by cutting, the common processing methods are milling, drilling, turning and so on. Cutting is the most important processing means of forming parts, which plays an important role in advanced manufacturing.

Inserts are used as cutting tools for cutting process but tool wear is unavoidable in the cutting process.

1. Introduction





1. Some surveys showed that 7-20% downtime in production and manufacturing process was caused by tool failure [1], which resulted in a significant loss in productivity and operation cost.

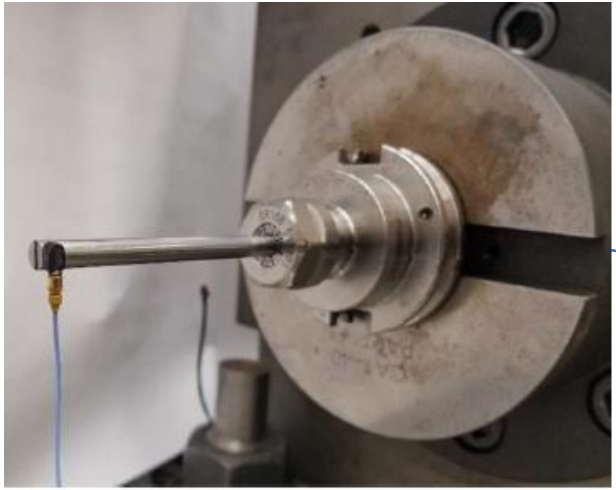
2. In addition, excessive tool wear seriously affects the quality of the manufactured component with decreased dimensional accuracy and increased surface roughness .

3. Therefore, it is of great importance to study appropriate tool condition monitoring (TCM) methods to maximize the usage of the cutting tool while not affecting the quality of manufactured parts.

1. Introduction

Tool Condition Monitoring Methods

Direct method	Indirect method
• Optical microscope • Vision sensor • Surface roughness instrument • Scanning electron microscope(SEM) • Energy-dispersive X-ray spectroscopy(EDS)	• Temperature • Cutting power • Spindle current • Vibration signals • Acoustic emission signals

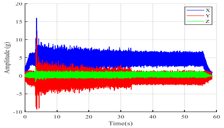


On-Rotor Sensing

ORS

2. CNC lathe system with ORS

2.1 Experimental setup

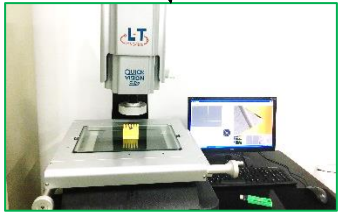


Vibration signals

ORS

Workpiece

CNC Lathe



Optical microscope system

Tool	**NX2525** $r_{\varepsilon}=0.4mm$
Material	**A3#steel(Q235)**
Cutting conditions	**Spindle speed： 1000rmp** **Feed rate：** **0.15mm/r*1000r/min=150mm/min** **Depth of Cut: 0.5mm, 1mm**
Motor model	**YVP112M-50-B5; 4kW; 50Hz**
Turning methods	**Cutting with coolant**

2. CNC lathe system with ORS

2.2 Static cutting force model

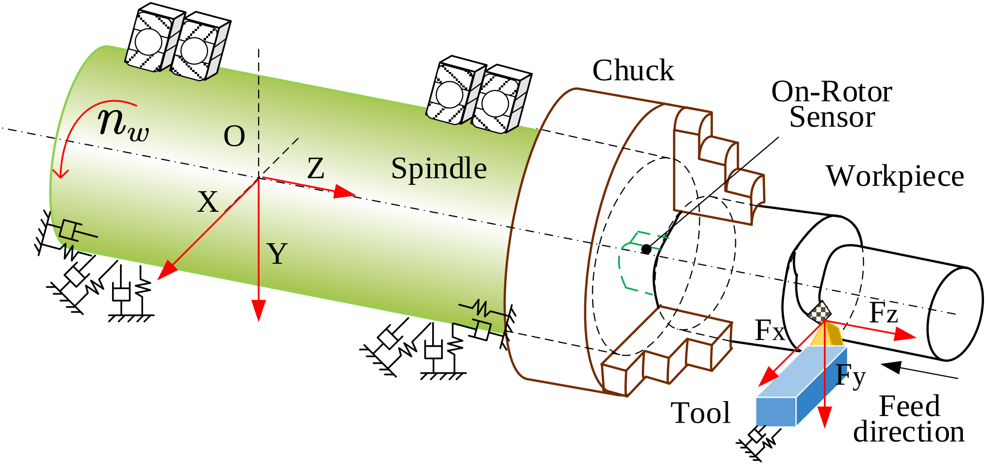


Figure .Cutting model of the CNC lathe system

The cutting forces are projected to the machine tool coordinate system as follows:

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \begin{bmatrix} 0 & -\sin\psi_r - \cos\psi_r & 0 \\ -1 & 0 & 0 \\ 0 & -\cos\psi_r & \sin\psi_r \end{bmatrix} \begin{Bmatrix} cos\gamma \\ cos\gamma tan\beta_a \\ cos\gamma tan\beta_r \end{Bmatrix} F$$

In Eq., where

ψ_r the angle between the direction of the cutting speed and the shear plane.

γ is the rake angle of cutting tool,

β_a is tool-chip frictional angle for rake face textured cutting tools

β_r is groove inclination angle. These angels can be expressed by coefficients.

$$cos\gamma = 1 \Big/ \sqrt{1 + \left(\frac{K_{fc}}{K_{tc}}\right)^2 + \left(\frac{K_{rc}}{K_{tc}}\right)^2}$$

$$tan\beta_a = \frac{K_{fc}}{K_{tc}}$$

$$tan\beta_r = \frac{K_{rc}}{K_{tc}}$$

2. CNC lathe system with ORS

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2.3 dynamic cutting force model

Variations in dynamic cutting force are derived from real-time changes in chip thickness, feed speed and cutting speed. Therefore, it can be known that the cutting vibration of dynamic cutting force is a periodic cycle process with the spindle rotating speed n_ω

The dynamic cutting force could be expressed by：

$$m_x\ddot{x}(t)+c_x\dot{x}(t)+k_x x(t)=K_x F(t)$$

$$m_z\ddot{z}(t)+c_z\dot{z}(t)+k_z z(t)=K_z F(t)$$

To reduce the number of parameters, tool and workpiece are assumed symmetric, i.e. $m_x=m_z=m, c_x=c_z=c, k_x=k_z=k$

The corresponding natural frequency is $\omega_n=\sqrt{k/m}$

and the damping ratio is $\zeta=c/(2m\omega_n)$

Eq. can be in a normalized expression：

$$\ddot{x}(t)+2\omega_n\zeta\dot{x}(t)+\omega_n{}^2 x(t)=\frac{K_x}{m}F(t)$$

$$\ddot{z}(t)+2\omega_n\zeta\dot{z}(t)+\omega_n{}^2 z(t)=\frac{K_z}{m}F(t)$$

Instantaneous total cutting force $F(t)$

can be obtained by an empirical formula:

$$F(t)=K_c h(t) w(t)^q$$

The cutting thickness $h(t)$ and cutting width $w(t)$

is affected by fluctuation of vibration in X-direction and Z-direction respectively, its instantaneous value is expressed by

$$w(t)=z_0-z(t)-z(t-\tau)$$

$$h(t)=x_0-x(t)-x(t-\tau)$$

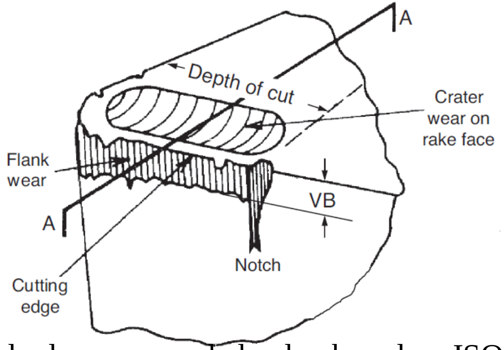
2. CNC lathe system with ORS

2.4 Tool wear

(3) When considering tool wear, there is additional cutting force :

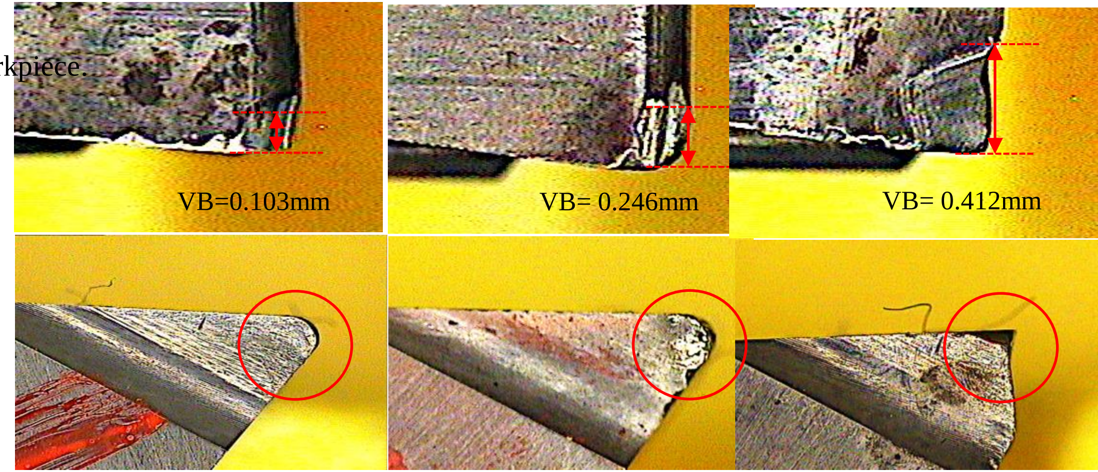
$$\triangle F=\mu \cdot H \cdot VB \cdot s$$

ΔF——Friction between the tool and the workpiece due to wear.
μ——The sliding friction coefficient between the tool and the workpiece.
H——Brinell hardness of workpiece material.
s——The length of the wear band on the flank of the tool.
VB——The amount of wear on the flank surface of the tool.



VB is a standard recommended value based on ISO 3685:1993.

Before the turning operation, the wear on the flank face of different inserts was measured by a optical microscope at 29.2 times magnification.



Break-in Tool　　Steady Tool　　Failure Tool

3. Results and discussion

(1) Raw vibration data from ORS

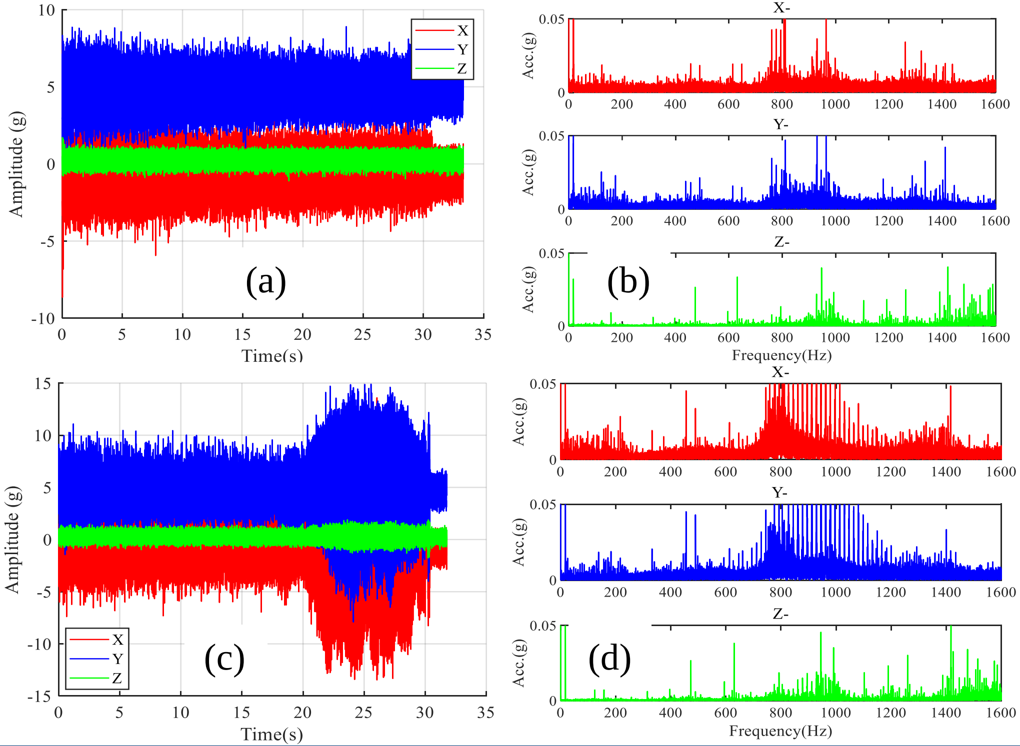


Figure (a) and (b) is the data from steady tool cutting and Figure (c) and (d) is the data from failure tool cutting. DOC=1mm, diameter of workpiece=35mm.

The vibration amplitude in X and Y direction is much larger than that of Z direction, showing that the diameter vibration and tangential vibration contains more information. Therefore, only the vibration signal in in X and Y direction are studied in this paper.

The amplitude of failure tool is much larger than that of steady tool, especially for the signal at the end of the cutting where chatter occurred.

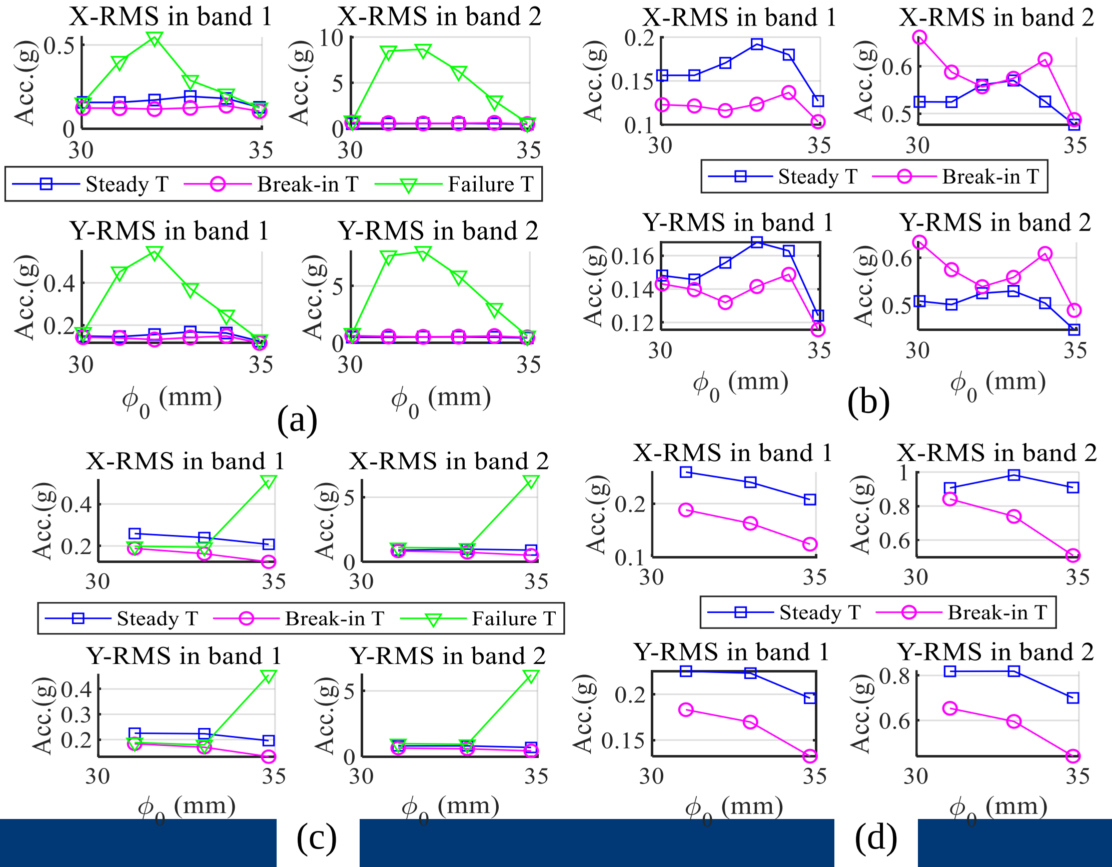
Resonance can be observed in the frequency band around 500Hz, 800Hz and 1000Hz. The resonance of these frequency bands is chosen as frequency bands for filtering in RMS method and spectral centroid analysis.

3. Results and discussion

(2) ***RMS analysis method***

Root mean square (RMS) values are extracted as critical features for online tool condition monitoring and diagnosis. G. Litak[28] stated that the increasing cutting depth leads to higher values of cutting forces components and higher fluctuation, and hence the severity of the fluctuation could be measured by RMS of the vibration signals.

Two filters in the frequency band 1 of 400Hz-500Hz and frequency band 2 of 700 Hz-1100Hz, in *X* and *Y* direction are adopted. two different cutting depths of 0.5mm and 1.0mm are set. The RMS of DOC of 0.5mm and of 1.0mm is shown in Figure (a), (b), (c) and (d) respectively.

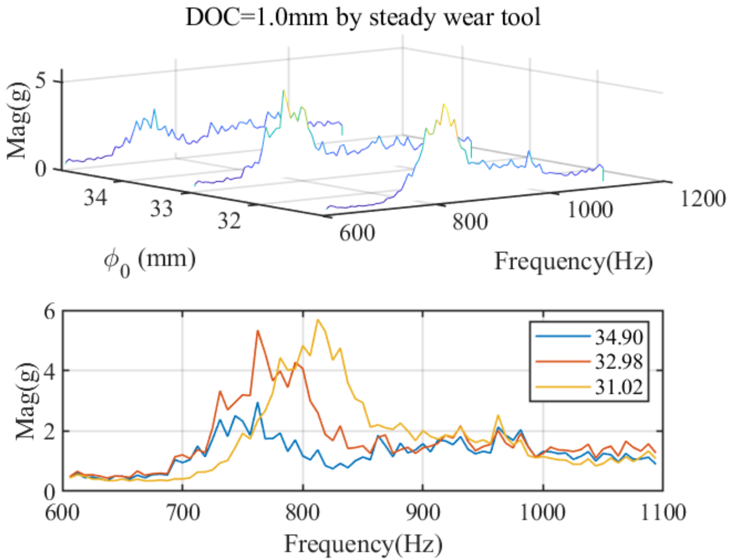


3. Results and discussion

(3) *Spectral centroid analysis*

It is known that the workpiece is tightly clamped by the chuck and the mass of workpiece keeps decreasing during the turning process. Therefore, the pitching natural frequency of the system will increase during the turning process in the Multi-Degree-of-Freedom (MDOF) system combining workpiece, chuck, spindle, and machine tool constitute.

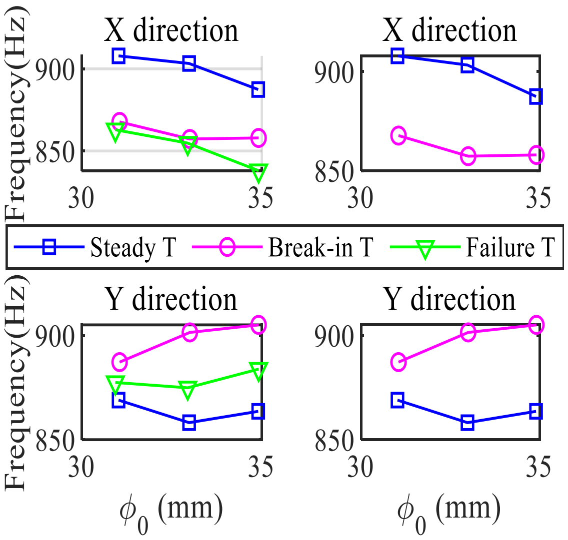
Figure shows a sample of frequencies in frequency band of 600Hz-1100Hz .



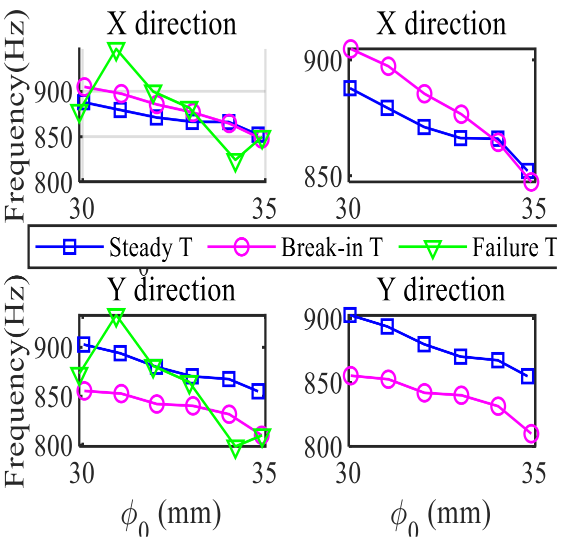
The spectral centroid increases during the cutting process. Therefore, this experiment only focuses on resonant frequency band when using spectral centroid method.

3. Results and discussion

(3) *Spectral centroid analysis*



(a) DOC=1.0mm



(b) DOC=0.5mm

As for the DOC=1.0mm, the spectral centroid in the *X* direction increases with the decrease of workpiece diameter for both tools which is consistent with previous analyses results.

When DOC=0.5mm, it also has a good recognition result.

In general, the spectral centroid method can be based on for effectively identification of different tool wear states for both DOCs.

4 . Conclusions

(1) A novel ORS which can be mounted on workpiece directly and rotates with it and the data obtained by ORS is more accurate and could better reflect the signal of each component in the actual CNC lathe processing system.

(2) This is accounted by direct sensing the vibration systems and characterizing the modal responses that are sensitive to frictional stochastic excitation during the turning process. Spectrum Centroid of vibration in the resonant frequency bands increases steadily with the progression of the cutting process as the mass of workpiece keeps decreasing.

(3) Finally, different tool states are identified by calculating the RMS and Spectrum Centroid after filtering.

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