



Research Paper

Rapid online detecting method of circular saw blade wear

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ABSTRACT

A circular saw blade wear measuring method is proposed based on line segment detection according to the geometric meaning of circular saw blade wear parameters in order to measure wear of circular saw blade on line. First, the pixel-precise edge in the binary image is extracted by edge tracking algorithm. Second, the line segment of edge in the image is detected by line segment detection algorithm. Finally, the information of line segments and least square method are used to calculate wear rate and compensation quantity of circular saw blade. In the line segment detection algorithm, the line segment is extracted firstly according to the chain code value of main direction and deputy direction and the length of line segment elements. Then, the rake face and rear face line segment are detected based on their features, at the same time deletes trashy and pseudo line segment. The algorithm omits the much angle calculation and reduces the time of detection. To evaluate the correctness of the algorithm, a worn circular saw blade is measured with the algorithm proposed in this study and traditional method respectively. The results are compared. The differences of the circular saw blade initial radius, R_0 , the average wear of front blade, SF , the average wear of back blade, SB , the average negative space, H , the radius, R , the tool compensation are 0.01%, 3.44%, 0, 0, 0.01% and 2.70%, respectively. The experiments show that the proposed method can detect wear rate and compensation quantity of circular saw blade quickly and accurately.

Jiyang Qi^{1,2*} and Qian Wu¹

¹School of Mechanical Engineering, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, 212003, China.

²Jiangsu Key Laboratory of Recycling and Reusing Technology for Mechanical and Electronic Products, Changshu 215500, China.

*Corresponding author. Email: jqqi@just.edu.cn.

Key words: Circular saw blade, wear detection, computer vision, edge tracking, line segment detection.

INTRODUCTION

Circular saw blade is a main tool used in cutting wooden materials, such as fiber board, glass fiber and magnesium cement board and plywood. The degree of wear of the blade is an important factor that affects the quality and efficiency of the process. So it is valuable and meaningful to explore the way of circular saw blade wear detecting on line and compensate the wear through adjusting the blade's relative position to the plate to be cut by micro displacement mechanism according to the detecting result, which will greatly lower machining error.

In the traditional method of tool wear detection, a tool microscope is used to detect the rate of wear, however the tool or blade will need to be disassembled in each

examination through this method, the tool needs to be clamped and set in position again after its examination, which makes the whole detection process time-consuming (Jiang et al., 2010), and cannot realize online detection of tool wear.

At present, the tool wear detection can be classified into indirect detection method and direct detection method. Indirect detection method gets wear of the blade through measuring the change of the physical quantity, such as cutting force, torque, temperature, sound radiation, etc. which is closely related to the tools condition during the cutting process. Indirect detection includes four methods as follows. 1) The tool wear is measured through vibration

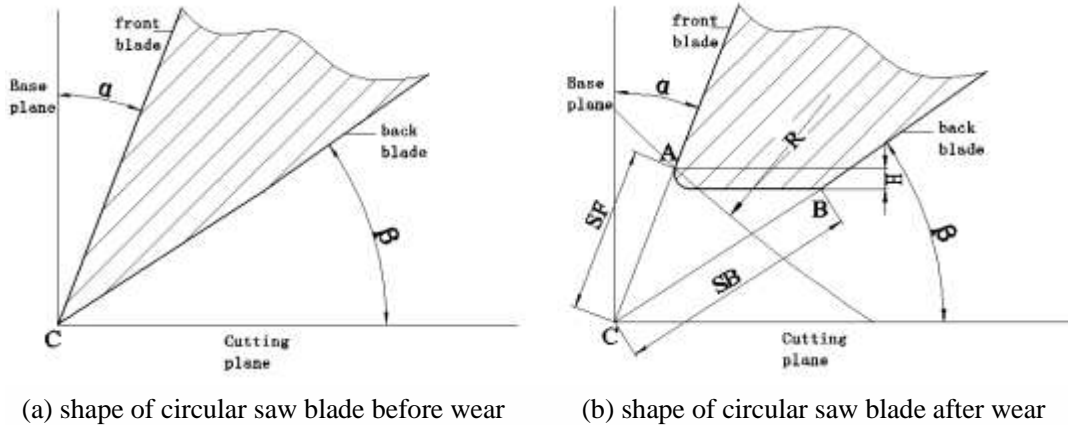


Figure 1: The geometric parameters of tool wear.

signal and motor current signal, which need to monitor vibration signal and motor current signal, the relationship between them and the tool wear rate need to be constructed, and then the tool wear condition is detected (Qi et al., 2015); 2) The tool wear is measured through cutting force, which need to monitor the change of the cutting force, the relationship between the cutting force and the tool wear rate need to be constructed, thus the tool wear condition is detected; 3) The tool wear is measured through noise, which need to monitor acoustic emission signal during the processing and the relationship between acoustic emission signal and tool wear rate is established, the tool wear condition is detected (Zhang et al., 2014); 4) The tool wear is measured through machined surface properties and quality, which need to monitor machined surface quality, then the wear of the blade is detected qualitatively according to the principle that the more serious the wear of the blade is, the poorer the machined quality is (Zhang et al., 2011; Shahabi and Ratnam, 2009). All these methods can only estimate tool wear qualitatively. Direct detection method is to detect tool wear by detecting the shape of the cutting edge or the change of position. It is to observe the state of the tool wear directly by using machine vision or optical microscope generally (Yu et al., 2014), and then use the appropriate algorithm to process the image to obtain the tool wear rate directly.

In recent years, online detection based on machine vision technology has been widely used in the fields of size, displacement and surface shape detection (Qin et al., 2014). There are two ways of using machine vision to detect tool wear (Mook et al., 2009). One is to detect the tool wear based on the image of the surface of the workpiece. The other is to detect the tool wear based on the image of the tool itself, which extracts the region of tool wear by using image processing technology, and calculates the geometric parameters of tool wear.

The methods mentioned above are also frequently used to detect circular saw blade wear. Zhao et al. (2010) established measurement system of geometric parameters

of circular saw blade based on machine vision. Based on the circular saw blade contour optimization, this method proposed the improved quadratic polynomial interpolation sub-pixel positioning method for locating the circular saw blade inner hole, and the two lines of tooth tips are fitted by the improved least square method, which has improved the detection accuracy. However, this method must get the whole image of circular saw blade, therefore it could not realize online measurement of circular saw blade wear. Ekevad et al. (2012) in Sweden constructed the relationship between circular saw blade wear and the vibration signal of blade during the process of sawing beech. Although this method has realized online measurement of the circular saw wear rate, it is still difficult to find the exact quantitative relationship between circular saw blade wear and vibration signal of saw blade, which can only make the qualitative detection of saw blade wear.

DETERMINATION OF DETECTION INDEX

During cutting, the circular saw blade makes relative movement to workpiece. A is the most front point of the front blade, that is, the first point of the cutting edge to cut the workpiece. B is the contact point of the back blade and the workpiece. C is the ideal tool-tip point. The wear rate of the front blade denoted by SF, wear rate of back blade denoted by SB and negative space denoted by H are introduced in the paper to measure the circular saw blade wear rate (Figure 1). The change quantity of the outer diameter of the circular saw blade, denoted by ΔR , is used to represent compensation quantity of circular saw blade wear (Geng, 2006).

DESIGN OF DETECTION ALGORITHM

According to the geometric meaning of these three blade parameters which are front blade wear rate, back blade

wear rate and negative space, tool wear detection can be transformed into line segment detection of digital image. This method is mainly divided into 3 steps: 1)The pixel-precise edge of the circular saw blade is extracted by using boundary tracking algorithm; 2)The target segment of the contour is extracted by the line segment element detection algorithm. The line segment is detected according to the chain code value of the main direction and deputy direction of the line segment. 3) The wear rate and compensation quantity of circular saw blade are calculated according to line segment information and image feature.

As it can be seen from Figure 1, the key problem to saw blade wear detection is the determination of the pixel-precise coordinates of each point A, B and C on the cutting edge of circular saw blades. The points A and B are endpoints of line segment of front blade and back blade, respectively and C is the intersection of the two line segments, so the main problem in image processing is to extract the line segment which can represent front blade and back blade of the circular saw blade.

Edge extraction

The important information related to the image processing is included in the contour of circular saw blade image. So, we need to extract image edge firstly. Because the image background collected by computer is white, while the circular saw blade is black, binary image of circular saw blade is obtained by the threshold segmentation method. And then the pixel-precise edge in the image is extracted by edge tracking algorithm (Li and Zou, 2015; Song et al., 2007). The specific process of edge tracking is given hereafter.

1). Determination of the tracking start point: Starting from the most top left corner of the image, scan the binary image of circular saw blade pixel by pixel from top to bottom, from left to right, and set the first pixel whose gray value is 1 as the starting point of boundary tracking denoted by P_0 .

2). Determination of the tracking rules: Use variable D_b to represent the initial searching direction of the next boundary point starting from the reference point, and D_e to represent the true direction of the next boundary point relative to the reference point. D_b and D_e use a digit between 0 and 7 to represent the location of pixel point relative to reference point with Freeman 8 neighborhood chain code coding method, as shown in Figure 2 (Song et al., 2007).

For any one edge of the image, as shown in Figure 3, when taking P_0 as the reference point to search the next boundary point P_1 , starting point P_0 is searched from top to bottom, from left to right, so P_1 cannot appear in the 2,3,4,5 direction of P_0 , otherwise P_0 is not the tracking starting point. Supposing the initial tracking direction $D_{b_0}=7$, search

in the counter clockwise direction, the direction value D_{e_0} of P_1 relative to P_0 is 7. When taking P_1 as the new reference point to search the next boundary point P_2 , the point P_2 cannot appear in the 3 or 4-point direction of the P_1 , making the initial tracking direction $D_{b_1}=5$, search in the counter clockwise direction, the value D_{e_1} of P_1 relative to P_0 is 6. Therefore, the following recursion formula is obtained:

$$D_{b_i} = \begin{cases} (D_{e_{i-1}} + 6) \% 8, D_{e_{i-1}} \text{ is an odd number} \\ (D_{e_{i-1}} + 7) \% 8, D_{e_{i-1}} \text{ is an even number} \end{cases}, \quad i = 1, 2, 3 \dots \quad (1)$$

3). Determination of termination conditions: Determine the current pixel coordinates of the boundary points. If the column coordinates X of the boundary point is equal to the number of column of the images, it means search has reached the image border, then stop searching.

Line segment detection

Definition 1: When using Freeman 8 neighborhood chain code to represent digital line segment, the collection of the continuous pixel points with the same chain code value is called line segment elements.

Digital line segments include 5 line segment elements a, b, c, d, and e in Figure 4. In each line segment element, the first pixel's chain code value is different from that of the line segment elements, but they have the same direction. The pixel point is the starting point of the line segment elements, and its chain code value indicates the deviated direction of the line segment elements relative to the previous line segment element. Therefore, we mark the chain code value of the line segment element as the main direction of the line segment element, and mark the chain code value of the starting point as the deputy direction of the line segment element (Molina et al., 2013; Elaksher, 2012).

According to the above regulations and Freeman digital line criterion, the following conclusions can be drawn:

- 1) All the line segment elements which form a digital line segment have the same main direction.
- 2) The deputy direction of the line segment elements which form a digital line segment is the same except the first line segment element.
- 3) Except the first and last line segment elements, the difference in the length of other line segment elements will be not more than 1 pixel in the digital line segment element.

Based on the above conclusions, a line detection algorithm is proposed in the study. Line segment elements in the

3	2	1
4	P	0
5	6	7

Figure 2: Freeman 8 neighborhood chain code.

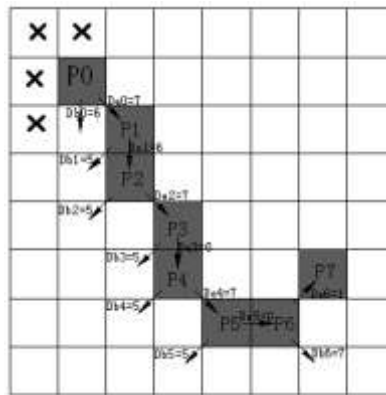


Figure 3: Schematic diagram of boundary tracking.

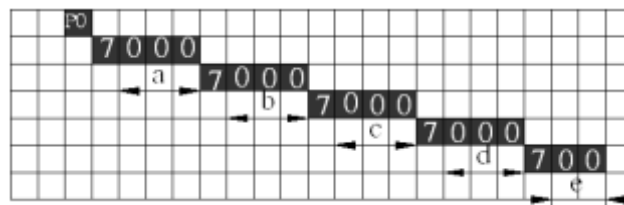


Figure 4: Digital line and line segment.

image boundary are searched with the algorithm according to the definition of line segment elements firstly, then initial line segment of boundary is detected according to the chain code value of main direction and deputy direction of line segment elements. At last, several line segments will be merged into a line segment according to parameters information such as angles and distance between line segments (Shang et al., 2005; Murshed et al., 2011). The whole algorithm implementation process is as follows:

- 1) The 8-neighborhood chain code of Freeman is used to encode the image boundary.
- 2) The line segment elements are searched in image

boundary, and the line segment elements are saved in the cell array Line-Cell. The elements in the cell array Line-Cell include starting point coordinate, the chain code value of main direction, the chain code value deputy direction and the length.

- 3) In the Line-Cell, continuous line segment elements whose chain code value of main direction and deputy direction are the same, and length of the difference is less than 2 are merged into a line segment and saved in the cell array Line. The elements in the cell array Line include: the index number of initial line segment element, the index number of the end line segment element, the chain code value of main direction and the chain code value of deputy

direction.

4) To determine whether the line segment in the Line array can extend to both ends. Line segment elements connected with the endpoints of the line segment should be scanned, if the line segment elements' main direction chain code value is the same with that of the line, then, continue to determine whether to extend according to the following criterion 1. If not, the line segment cannot be extended.

Criterion 1: The coordinates of starting point and the endpoint of the line segment L_1 are assumed as (x_{1b}, y_{1b}) and (x_{1e}, y_{1e}) in the cell array Line. The coordinates of starting point and endpoint of line segment element connected with line segment L_1 are assumed as (x_{2b}, y_{2b}) and (x_{2e}, y_{2e}) . Original line segment slope is:

$$K_{L1} = \frac{y_{1e} - y_{1b}}{x_{1e} - x_{1b}} \quad (2)$$

If the line segment element is connected with the starting point of the line segment L_1 , then the new line segment slope is:

$$K_{L2} = \frac{y_{2b} - y_{1b}}{x_{2b} - x_{1b}} \quad (3)$$

If the line segment element is connected with the endpoint of the line segment L_1 , then the new line segment slope is:

$$K_{L2} = \frac{y_{2e} - y_{1b}}{x_{2e} - x_{1b}} \quad (4)$$

If $|K_{L1} - K_{L2}| < \theta$, line segment is judged to be possible to extend. The information of the line segment is updated and saved in the cell array Line. Theta (θ) is a set threshold which determines the accuracy of line segments detection.

5) The parameter information of line segment, such as slope k and intercept b , is calculated according to the coordinates of line segment endpoints, and then according to the criterion 2 to determine whether the line segment can be merged with other line segments whose main direction's chain code value are the same. If they can be merged, then the parameter information of the line segment is combined and updated.

Criterion 2: The parameter information of the two line segments L_1 and L_2 which have the same the main direction chain code value is assumed as $[k_1, b_1, (x_{b1}, y_{b1}), (x_{e1}, y_{e1})]$ and $[k_2, b_2, (x_{b2}, y_{b2}), (x_{e2}, y_{e2})]$ respectively. If the parameters of the two line segments meet the following three conditions at the same time, then the two line

segment can be merged:

$$\sqrt{(x_{e1} - x_{b2})^2 + (y_{e1} - y_{b2})^2} < T_1 \quad (5)$$

$$|k_1 - k_2| < T_2 \quad (6)$$

$$|b_1 - b_2| < T_3 \quad (7)$$

where, T_1, T_2, T_3 are the distance threshold of the two segments, the slope threshold and intercept threshold, respectively and they can determine the accuracy of line segment detection.

6) To avoid the interference signal, the line segment whose length is less than the threshold value T_4 is deleted.

Target location

After the above processing, the line segment of the circular saw blade contour has been extracted but the location of cutting edge points A and B cannot be determined yet. Point A and B are the endpoints of the front blade and back blade of the same cutting tooth, respectively. To determine the coordinates of point A and B, among the line segments which have been extracted, we must determine the exact line segment of the front blade and the line segment of the back blade. It is not difficult to find that front blade line segment and back blade line segment of circular saw blade are alternate through observing the image of the circular saw blade. Because the algorithm records boundary points in sequence, what needs to be done is to determine the properties of the first line segment. Then, according to some criteria, the properties of the remaining line segment can be deduced, thus the coordinates of point A and B on each cutting edge are determined.

The endpoint coordinate of first line segment in a cell array Line is assumed as (x_{e1}, y_{e1}) . The analytic formula is $y_1 = k_1x + b_1$. The analytic formula of the second line segment is $y_2 = k_2x + b_2$. The intersection longitudinal coordinate of two line segments is $y = k_1(b_2 - b_1) / (k_1 - k_2) + b_1$. If $y < y_{e1}$, the first line segment and the second line segment belong to the same saw tooth and the intersection is ideal tool-tip point. If $y > y_{e1}$, the first and the second line segments do not belong to the same saw tooth, while the second and the third line segments belong to the same saw tooth. Then the properties of the line are determined further according to the characteristics of the obtained circular saw blade image. If the circular saw blade cuts the workpiece by counterclockwise rotation in the image, the small label number line segment between the two-line segments which belong to the same saw tooth represents back blade and the large label number line segment represents front blade. If the circular saw blade cuts workpiece by clockwise rotation

the image, the results are opposite.

Solution of wear rate

The coordinates of all the point A of different blade are assumed as $\{(x_{A1}, y_{A1}), (x_{A2}, y_{A2}) \dots (x_{An}, y_{An})\}$ by the detection algorithm and the coordinates of point B are assumed as $\{(x_{B1}, y_{B1}), (x_{B2}, y_{B2}) \dots (x_{Bn}, y_{Bn})\}$. The analytic formulas of front blade and back blade are $y_{1i} = k_{1i}x + b_{1i}$ and $y_{2i} = k_{2i}x + b_{2i}$ respectively, where $i = 1, 2, \dots, n$. The calculation methods of each parameter are as follows:

1) The coordinate of ideal tool-tip point C

$$x_{Ci} = \frac{b_{2i} - b_{1i}}{k_{1i} - k_{2i}}, y_{Ci} = k_{1i} \frac{b_{2i} - b_{1i}}{k_{1i} - k_{2i}} + b_{1i} \quad (8)$$

2) Wear rate of front blade, SF

$$SF = \frac{\sum_{i=1}^n \sqrt{(x_{Ai} - x_{Ci})^2 + (y_{Ai} - y_{Ci})^2}}{n} \quad (9)$$

3) Wear rate of back blade, SB

$$SB = \frac{\sum_{i=1}^n \sqrt{(x_{Bi} - x_{Ci})^2 + (y_{Bi} - y_{Ci})^2}}{n} \quad (10)$$

4) Negative space, H

$$H = \frac{\sum_{i=1}^n y_{Ai} - y_{Bi}}{n} \quad (11)$$

5) Compensation quantity of the tool, ΔR

$$\Delta R = R_0 - R \quad (12)$$

R_0 is the radius of circular saw blade before cutting and R is the radius of circular saw blade after cutting. R_0 and R can be obtained by using the least-squares circle fit based on the coordinates of point A, $\{(x_{A1}, y_{A1}), (x_{A2}, y_{A2}), \dots, (x_{An}, y_{An})\} (n > 3)$.

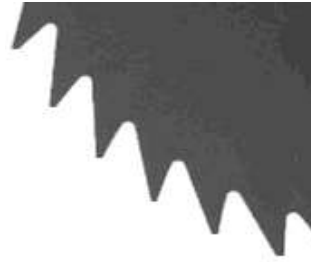
THE CASE STUDY OF SAW BLADE WEAR DETECTION

To verify the validity and the real-time of the algorithm, an experiment of saw blade wear detection is designed in the paper. An ordinary circular 40-tooth tungsten saw blade is taken as the research object, with 200 mm in outer diameter and 1.4 mm in thickness. Glass fiber and magnesium cement board is chosen as workpiece.

Experimental apparatus included PCA-6010VG Industrial Personal Computer (IPC) made in Advantech, PCI-1426 NI image acquisition card, Pantera1M30 monochrome camera made in Teledyne DALSA (resolution ratio is 1024*768) and mml4-195d Industrial micro lens (magnification times is 4) and LED lights, etc. The diffuse reflection of backlight is adopted, which the light source and the camera are mounted on both sides of circular saw blade respectively and perpendicular to circular saw blade. After the equipment is installed, the camera is calibrated and the calibration result is 35.7 $\mu\text{m}/\text{pixel}$. Thereafter, the location of the device is no longer adjusted, otherwise, the camera must be calibrated again. The image of the circular saw blade should be collected first before cutting, and then the initial radius R_0 and the center coordinate of the circular saw blade are calculated. The wear of circular saw blade occurs after cutting the workpiece for some time. Figure 5 shows the detection results of the image. The whole detection process consumes 0.227s. The calculation results of the detection algorithm are shown in Table 1. To verify the correctness of the algorithm, the traditional measuring method is used to measure the worn circular saw blade. Comparison between the two methods is made. As can be seen from Table 1, the measured values of the two methods are very close. Thereby, the correctness and validity of the algorithm proposed in this study have been verified.

CONCLUSION

According to the geometric feature of circular saw blade wear parameters, the tool wear detection algorithm has been proposed based on line detection in the study. This algorithm extracts the pixel-precise boundary of the circular saw blade in binary image firstly by using the boundary tracking algorithm. Then the line segment in circular saw blade image is extracted using new line segment detection algorithm. Finally, the pixel-precise coordinates of the target points are determined according to the feature of the image and information of line segments, so the wear rate and the compensation quantity of tool are obtained. Through the experiment, a worn circular saw blade is measured with the algorithm proposed in this study and the traditional method, respectively. The differences in the circular saw blade initial radius, R_0 , the average wear of front blade, SF , the average wear of back blade, SB , the average negative space, H , the radius, R , and the tool compensation are 0.01%, 3.44%, 0, 0, 0.01% and 2.70%, respectively. Experimental results show that the compensation quantity and wear rate of circular saw blade can be detected rapidly and accurately with this method. Boundary tracking algorithm makes use of the changing initial direction to reduce the judgment times of boundary points greatly. Line segment detection algorithm abandons a lot of angle calculation, which makes the whole detection algorithm have good real-time performance, strong anti-interference



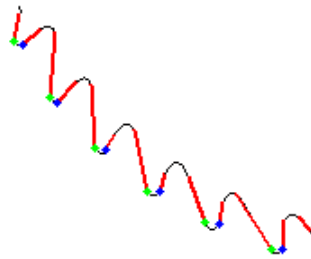
(a) Original image



(b) Binary image



(c) Boundary image



(d) Detecting result

Figure 5: The experimental results of cutting circular saw blade wear detection.

Table 1: Comparison of results from the different methods.

Parameter	Calculation results (mm)	Measured results (mm)	The difference of two method (%)
Circular saw blade initial radius, R_0	99.99	100.01	0.02
The average wear of front blade, SF	0.30	0.29	3.44
The average wear of back blade, SB	0.28	0.28	0
The average negative space, H	0.06	0.06	0
The present radius of circular saw blade, R	99.63	99.64	0.01
The compensation quantity of tool	0.36	0.37	2.70

ability and high detection precision. It can be extended to wear detection of other types of tool.

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