Investigation on the vibration characteristics of circular saw blade with different slots

Wei Feng1,2,3, Jinheng Zhang1,2,3,4, Haoren Zhou1,2,3 and Hao Di1,2,3

1 School of Mechanical Engineering, Shandong University, Jinan 250061, China
2 Key Laboratory of High-Efficiency and Clean Mechanical Manufacture (Ministry of Education), School of Mechanical Engineering, Shandong University, Jinan 250061, China
3 Research Centre for Stone Engineering (Shandong Province), Jinan 250061, China
4 E-mail: zhangjs@sdu.edu.cn

Abstract. Irregular vibration of circular saw blade caused by complex forces in the process of cutting harms the operators, product quality and the life of circular saw blade. In this paper, the modal analysis of circular saw blades with different slot length and four kinds of unequal slot length saw blades are carried out based on the finite element theory. The vibration characteristics of circular saw blades with different slot length is studied. The results show that the natural frequency and the maximum deformation increase with the increasing slot length. In the case of higher order after the 5th order, the phenomenon is even more obvious. The effects of slot length, slot depth and diamond segment on natural frequency are compared. The results show that slot length has the greatest effect on natural frequency. Circular saw blades of different structures with unequal slot length can be selected to avoid resonance during operation.

1. Introduction

With the development of industrial modernization, the application scope of circular saw blade is expanding. As an important tool in the field of cutting and processing, circular saw blade is mainly used in the processing of hard materials [1]. However, irregular local transverse vibration is caused by the interaction between the circular saw blade and the workpiece in high speed cutting [2]. The vibration produces noise and transverse vibration displacement, which affects the sawing precision and the surface roughness of the workpiece. In addition, it has a negative impact on the health of the operator and the working life of circular saw blade [3]. It has become an important research field to study the vibration damping principle and noise damping of circular saw blade [4, 5].

The vibration of circular saw blade has been studied by many scholars. The vibration forms of circular saw blade have been mainly divided into transverse vibration, radial vibration and torsional vibration. Slotted circular saw blade, composite circular saw blades and On-line vibration control technology of circular saw blade has been proved to control circular saw blade noise and vibration effectively [6-9]. Zhang et al studied the natural frequency of slotted circular saw blade by using orthogonal experiment. In addition, they studied the influence of slot on the natural frequency of saw blade, and compared the vibration characteristics of the composite damped circular saw blade with that of the ordinary circular saw blade based on finite element method (FEM). The natural frequency and maximum deformation displacement of the composite damped circular saw blade has been proved
to be less than that of the ordinary circular saw blade in the corresponding order [10, 11]. Li et al used FEM to analyze the factors affecting the natural characteristics of saw blades, and concluded that the natural frequency of saw blade increases with the increase of thickness, rotation speed and clamping ratio, but decreases with the increase of saw blade diameter [12]. FEM in milling has been studied by many researchers. It proved that unequal tooth length can reduce vibration in milling effectively [13-16]. Yan et al studied the vertical milling cutter's with different tooth distances based on finite element method. The vibration characteristics of vertical milling cutter's with different tooth distances are studied [17]. Unequal slot length has been used in circular saw blades for cutting metal [18]. At present, the research focuses on the effects of conventional parameters such as the thickness, diameter and center hole of the saw blade on the natural frequency. There is few Investigation on the vibration characteristics of circular saw blade with different slots.

In this paper, diamond circular saw blades for stone are studied as an example. The structure of diamond circular saw blade as shown in Figure 1. Slot length represents the distance between two diamond segments. Slot length in circular saw blade for stone is similar to pitch in saw blade for metal. The modal analysis of circular saw blades with different slot length is carried out based on FEM, the vibration characteristics of circular saw blades with different slot length is studied.

![Figure 1. The structure of diamond circular saw blade.](image)

2. Theoretical analysis

The dynamic equation of circular saw blade is obtained as follows based on vibration theory and finite element theory [19]:

\[
\begin{bmatrix} M \end{bmatrix} \dddot{u} + \begin{bmatrix} C \end{bmatrix} \ddot{u} + \begin{bmatrix} K \end{bmatrix} \dot{u} = \begin{bmatrix} F \end{bmatrix}
\]

\( (1) \)

\([M]\) represents the mass matrix. \([C]\) represents damping matrix. \([K]\) represents stiffness matrices. \(\dddot{u}, \ddot{u}, \dot{u}\) respectively represent the structural acceleration vector, the velocity vector, the displacement vector. \(\{F\}\) represents the load vector changed with time.

When \(\{F\} = \{0\}\), the natural frequencies and modes of the circular saw blade are obtained. Material damping are not considered in the modal analysis. The vibration of a circular saw blade can be thought of harmonic vibration. The eigenvalue equation is obtained as follows [20]:

\[
\begin{bmatrix} K \end{bmatrix} - w_i^2 \begin{bmatrix} M \end{bmatrix} \{u\} = 0
\]

\( (2) \)

Where, \(w_i\) is the natural frequency of the \(i\) th order, \(i=1, 2, \ldots, n\).

The dynamic equation of circular saw blade is converted from physical coordinate system to modal coordinate system. The vibration displacement is obtained.

\[
\{u\} = \Phi \{\eta\} = \phi_1 \{\eta_1\} + \cdots + \phi_n \{\eta_n\} = \Phi \{\eta\}
\]

\( (3) \)
Where, \( \{ \eta \} = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \vdots \\ \eta_n \end{bmatrix} \) stands for a vector composed of modal participation factors.

Then the speed of circular saw blade in the physical coordinate system is

\[
\{ \dot{u} \} = jw \{ u \} = 2j\pi f \{ u \}
\]

The vibrational velocity of the \( r \) th order at point \( i \) of the structure

\[
\dot{u}_{r,i} = 2j\pi \eta_r \varphi_{r,i}
\]

Where: \( j \) represents a complex unit; \( \varphi_{r,i} \) represents the mode displacement of the \( r \) th order at structure \( i \).

Modal deformation needs to be normalized before comparison. The displacement of each node when resonance occurs can be compared based on normalization. In this paper, mass matrix normalization is chosen as the basis of normalization [21].

\[
\{ \phi \}^T \{ M \} \{ \phi \} = 1
\]

The orthogonality of the feature vectors is guaranteed. It is convenient for spectrum analysis and mode superposition analysis.

3. Effect of slot length of circular saw blade on natural frequency

3.1. The effect of uniform slot length on natural frequency

Five schemes of circular saw blade with different slot length were established to analyze the influence of slot length on the natural frequency of circular saw blade. The specific structure of circular saw blade is shown in Table 1.

| Scheme | Diameter | Thickness | Center hole | Slot length |
|--------|----------|-----------|-------------|------------|
| 1      | 780      | 5.5       | 50          | 8          |
| 2      | 780      | 5.5       | 50          | 16         |
| 3      | 780      | 5.5       | 50          | 24         |
| 4      | 780      | 5.5       | 50          | 32         |
| 5      | 780      | 5.5       | 50          | 40         |

Saw blade matrix, whose material is 75cr1, density is 7850 kg/m³, elastic modulus is \( 2.44 \times 10^{11} \) N/m², Poisson ratio is 0.3. The relationship between the number of mesh and the accuracy is considered. The mass distribution and stiffness distribution of the structure determine the natural frequency and the main mode. Since there is no stress concentration, the uniform mesh can make the element difference between the stiffness matrix and the mass matrix small. According to the principle of finite element mesh division [22], the element type selected in this paper is tetrahedral mesh, with a maximum mesh size of 10 and a minimum mesh size of 2. The rotation speed of the circular saw blade is 1600rpm. The cutting force of the circular saw blade in working condition is taken as a reference. The load is applied to the edge of diamond segment. The value of tangential force is 50N, the value of normal force is 600N. Through the analysis of natural frequency and maximum deformation, the natural vibration characteristics of five circular saw blades were compared.

The variation of natural frequency with slot length under multilevel orders is shown in Figure 2. The natural frequency increased obviously with the slot length. In the case of higher order after the 5th order, the phenomenon is even more obvious. With the gradual increase of slot length, the natural frequency tended to be gentle and was less affected by slot length. Figure 3 shows the maximum deformation of five circular saw blades modal. The variation trend of the maximum displacement and
deformation of all five circular saw blades with different slot length was basically the same with the increasing order. The maximum deformation increased with the slot length.

**Figure 2.** The variation of natural frequency with slot length under multilevel orders.

**Figure 3.** The five circular saw blades modal vibration mode maximum deformation comparison.

**Figure 4.** The distribution of the maximum and minimum position of the sixth order vibration of circular saw blade with different slot length (1)-5 respectively represent the circular saw blade with slot length of 8, 16, 24, 32, 40).
The natural frequencies increase slowly in the first 5 orders, and the frequency increases significantly from the 6th order. The sixth order typical modes of the saw blades of each scheme are represented to discuss the most significant vibration. The most significant position of vibration is around the diamond segment with prestressing force applied, and the smallest position of vibration is at the central hole. Figure 4 shows the distribution of the maximum and minimum position of the sixth order vibration of circular saw blade with different slot length.

3.2. The effect of unequal slot length on natural frequency

The circular saw blade model with unequal pitch for metal were referenced. In order to analyse the vibration characteristics of the circular saw blades with unequal slot length, four schemes for circular saw blade structure were built based on the slot length of 8, as shown in Figure 5, and the specific structural of four unequal slot length circular saw blades are shown in Table 2.

![Figure 5. Four schemes for circular saw blade structure (a) The circular saw blade with the same slot length; b) Blade with change in slot length; c) Blade with change in diamond segment; d) Blades with peripheral slot of different depths).](image)

| Matrix diameter (mm) | Center hole (mm) | Matrix thickness (mm) | Slot length (mm) | Diamond segment (mm) | Slot depth (mm) |
|----------------------|------------------|-----------------------|-----------------|----------------------|-----------------|
| a                    | 780              | 100                   | 5.5             | 8                    | 22              | 14              |
| b                    | 780              | 100                   | 5.5             | 8/40                 | 22              | 14              |
| c                    | 780              | 100                   | 5.5             | 8                    | 22/54           | 14              |
| d                    | 780              | 100                   | 5.5             | 8                    | 22              | 14/24           |

Modal analysis was carried out on 4 circular saw blade schemes with unequal slot length. A fixed constraint was applied to the circular surface in the center hole of the circular saw blade matrix. The element type selected is tetrahedral mesh, with a maximum mesh size of 10 and a minimum mesh size of 2. The rotation speed of the circular saw blade is 1600rpm. The load is applied to the edge of diamond segment. The value of tangential force is 50N, the value of normal force is 600N. The first 20 orders natural frequencies and maximum deformation were extracted by modal calculation of 4 circular saw blades with unequal slot length. The result is shown in Figure 6.
Figure 6. The natural frequency and maximum deformation of four schemes circular saw blade.

In the first 20 orders, the natural frequencies of four circular saw blades with unequal slot length increase with the increasing order. The natural frequencies increase slowly in the first 5 orders, and the frequency increases significantly from the 6th order. Therefore, the sixth order typical modes of the saw blades of each scheme were analysed. The result is shown in Figure 7.

Figure 7. The sixth order typical mode pattern of the saw blade of each scheme (a) The circular saw blade with the same slot length; b) Blade with change in slot length; c) Blade with change in diamond segment; d) Blades with peripheral slot of different depths).

The natural frequency of circular saw blades with unequal slot length in schemes b was obviously greater than the natural frequency of circular saw blades corresponding to schemes a, c and d. There was little difference in natural frequency between scheme a and scheme c. The natural frequency of
scheme d is slightly less than the corresponding natural frequency of scheme a. The maximum displacement of the saw blade deformation in scheme b is greater than that in other schemes, and the deformation displacement of the saw blade in scheme c is the smallest. Compared with scheme a, scheme b and scheme c can be regarded as 16 sets of diamond segment, each set of 5 segments. Scheme b can be seen as one segment is removed in every five segments. The slot length has been taken as variable in the comparison scheme a and b. With the increase of slot length, the natural frequency of scheme b can be increased by 4% compared with that of scheme a, and the maximum deformation of scheme b can be increased by 6% compared with that of scheme a, which is consistent with the above simulation. Scheme c can be seen as two segments being combined into one for every five segments. The diamond segment has been taken as variable in the comparison scheme a and c. The results show that the change of diamond segment had little effect on the natural frequency and the maximum deformation. With the increase of diamond segment, the natural frequency of scheme c can be decreased by 0.5% compared with that of scheme a, and the maximum deformation of scheme c can be decreased by 0.6% compared with that of scheme a. The slot depth has been taken as variable in the comparison scheme a and d. The result shows that the natural frequency and the maximum deformation increase with the increasing slot depth. With the increase of slot depth, the maximum deformation of scheme d can be increased by 4.3% compared with that of scheme a, and the natural frequency of scheme d can be similar to scheme a.

4. Conclusions

In this paper, the investigation on the vibration characteristics of circular saw blade with different slots is studied, which provides reference value for improving the dynamic characteristics of circular saw blade. The circular saw blades with different slot length and four types of unequal slot length saw blades were modelled and simulated respectively based on the finite element theory.

The natural frequency was sensitive to the slot length of the circular saw blade. The natural frequency increased with the increasing slot length, and the slot length had a greater influence on the natural frequency after the 5th order. The maximum deformation increases with the increasing slot length, and the variation trend of different circular saw blades were basically the same. It indicated that the damping effect of the circular saw blades with small slot length is better. Reduction of vibration and deformation can be obtained with the reduction of slot length. On the premise of satisfying the normal cutting conditions and working conditions, the small slot length circular saw blade has the best damping characteristics and damping effect. The first 20 natural frequencies of four unequal slot length circular saw blades were analysed. It can be obtained that the vibration and damping characteristics of circular saw blade can be improved with unequal slot length. The influence of slot length on natural frequency was much greater than diamond segment. The influence of slot length on the natural frequency of circular saw blade is greater than the depth of slot. It is worth mentioning that order also has an influence to the dynamic characteristics of circular saw blade. In the first 20 orders, the natural frequencies of circular saw blades with different slot length increased with the increasing order. The natural frequencies of the first 5 orders increased slowly, and the natural frequencies increased faster from the order 6 to 20.

Acknowledgements

This work is supported by Taishan industrial leading talent project of Shandong Province, China (No. tscy20150228) and Shandong Key Research and Development Project (No. 2019GGX104022).

References

[1] Tillmann W 2000 Trends and market perspectives for diamond tools in the construction industry International Journal of Refractory Metals & Hard Materials 18 301-306

[2] Li L, Xi B T and Yang Y F 2002 The developments in the vibration, dynamic stability and control research of circular saw—the analysis on vibration and dynamic stability of circular saw Woodworking Machine Tool 02 5-10
[3] Nishio S and Marui E 1996 Effects of slots on the lateral vibration of a circular saw blade
International Journal of Machine Tools & Manufacture 36(7) 771-787

[4] Ji C H, Liu Z Q and Liu L N 2010 The research progress of circular saw blade noise and noise reduction technology Tool Technology 44(08) 3-7

[5] Ren J H, Tang X H, He Y Y, Zhou J X and Zhu G F 2003 Research on the mechanism of noise reducing of laser-slotted diamond circular saw blade Diamond and Abrasive Engineering (02) 33-35

[6] Liu S L and Han X B 2009 Noise of Tungsten Carbide Circular Saw Blades and Measures for Reducing Noise Forestry Machinery and Woodworking Equipment 37(07) 28-30

[7] Hong Y, He X D and Wang R G 2012 Vibration and damping analysis of a composite blade Materials & Design 34 98-105

[8] Gospodarič B, Bučar B and Fajdiga G 2015 Active vibration control of circular saw blades European Journal of Wood & Wood Products vol.73(2) pp 151-158

[9] Nabi S M and Ganesan N 1993 Vibration and damping analysis of pre-twisted composite blades Computers & Structures 47(2) 275-280

[10] Zhang M S 2014 Composite damping circular saw blade vibration characteristics analysis Applied Mechanics and Materials vol. 670-671 pp 1106-1111

[11] Zhang M S, Zhu P X, Ke J J and Zhu Y K 2013 Diamond circular saw blades noise attenuation and finite element modal analysis Applied Mechanics and Materials 444-445 pp 129-133

[12] Li Y and Xu X P 2015 Modal analysis of circular diamond saw-blade for deep sawing of granite Key Engineering Materials 315-316 pp 348-351

[13] Li H, Zhang Y P and Liu F L 2003 Study on the effect of a face-milling cutter with unequal blade spacing on vibration Mechanical Science and Technology 03 408-411+417

[14] Sellmeier V and Denkena B 2011 Stable islands in the stability chart of milling processes due to unequal tooth pitch International Journal of Machine Tools & Manufacture 51(2) 152-164

[15] Song Q H, Ai X and Zhao J 2011 Design for variable pitch end mills with high milling stability The International Journal of Advanced Manufacturing Technology 55(9-12) 891-903

[16] Wang Y, Gai X Z, Zhai Y S and Lu J H 2019 Prediction and verification of stability domain of plunge milling cutter with unequal pitch Tool Engineering 53(05) 14-19

[17] Yan K, Wang Y S, Zhang D S and Sun W 2014 Modal analysis and vibration reduction of end milling cutter with unequal pitch based on ANSYS Equipment Manufacturing Technology (11) 105-106

[18] Lv S H 2013 The research of noise and vibration control on variable pitch circular saw Yanshan University

[19] Li Q H, Tan Q C, Pei Y C and Wu L 2007 Finite element analysis of lateral vibration of high-speed rotating disk cutter slice blade Journal of Jilin University 37(4) 814-818

[20] Ge J Y, Huang B and Zhang J S 2016 Analysis on modal and frequency response of combined diamond circular saw blades Journal of North University of China (Natural Science Edition) 037(004) 375-380

[21] Lin X K, Qin B Y and Zhang L M 2012 Mass normalization of experimental modal shapes based on additional mass Journal of Vibration, Measurement & Diagnosis (05) 90-96+170

[22] Du P A 2000 The basic principle of finite element mesh division Machinery Design & Manufacture (01) 34-36