Optimization of diamond circular saw blade by vibration noise analysis

T Wu¹*, D Wang¹ and M Zhao¹,²

¹ Department of Intelligent, Shenyang City University, Shenyang City, China
² Shenyang Jianzhu University, Shenyang City, China

* 81836848@qq.com

Abstract. The vibration noise analysis and optimization of diamond circular saw blade is presented. The position of hole of the diamond circular saw blade matrix with diameter of 500 mm is established by analyzing the vibration and noise through experiment, and then making matrix topology optimization to the blade by ANSYS. The research content is divided into three parts. The noise analysis of diamond saw blade. Study on vibration characteristics of diamond saw blades. The optimization design of diamond saw blade. The study on the noise and vibration characteristics of diamond circular saw blade provides some reference for the design and technological parameter of blades. The successful application of the topology optimization has certain reference value to production and manufacturing of saw blades.

1. Introduction

Diamond circular saw blade [1] is the main tool for cutting stone, which is a thin plate tool with limited bending resistance. Moreover, because of its narrow sawing path, poor heat dissipation and uneven stress, thermal deformation and axial deformation often occur during operation, resulting in vibration [2]. If the vibration frequency is close to other external excitation frequencies, resonance will occur. If the vibration is too strong, noise pollution [3] will follow. The vibration and noise of diamond circular saw blades have serious adverse effects on operators, equipment and product quality. Therefore, analyzing the vibration and noise characteristics of diamond circular saw blades and trying to reduce the vibration and noise can improve the production quality and benefit people's health.

For now, most researches [4] on vibration and noise reduction of circular saw blades mainly focus on radial slots optimization and damping technology. However, the research on the internal structure of circular saw blade matrix, especially the method of determining the opening position [5] on the matrix, has rarely been reported in relevant literature.

Topology optimization technology has outstanding advantages in structural optimization, but few people had applied topology optimization technology in the structural optimization of saw blades. Therefore, topology optimization technology can also be used to study the optimization design of the substrate structure of circular saw blade.

In this study, a series of studies were carried out on the vibration and noise of diamond circular saw blades in use. The noise and vibration characteristics of diamond circular saw blade were analyzed through experimental [6] measurement results. The effects of saw blade structural parameters, cutting parameters and cutting materials [7] on saw blade noise were studied, and the natural frequencies and modal shapes of diamond circular saw blade were obtained. Under the condition of ensuring the stiffness...
of the saw blade, and without changing the whole manufacturing process of circular saw blade, the saw blade without holes in the matrix was optimized [8] through topology optimization technology, and the hole position on the saw blade matrix is determined and discussed in this paper.

2. Problem Description
In this study, the noise and vibration characteristics of diamond circular saw blade are analyzed, which is the theoretical basis for reducing noise and vibration of it. Topology optimization function of ANSYS Workbench [9, 10] was used, the topology optimization of diamond circular saw blade with no holes in the matrix was carried out, and the optimized diamond circular saw blade with a diameter of 500 mm was trial-manufactured. By measuring and comparing the noise value and natural frequency value of the diamond circular saw blade before and after optimization, which is used to verify whether the optimized diamond circular saw blade has certain vibration and noise reduction effect.

3. Experiment and analysis methods

3.1. The related basic theory vibration and noise
The vibration of diamond circular saw blade at work is usually [11] divided into transverse vibration, radial vibration and torsional vibration. As its thickness is much smaller than its diameter, so its bending stiffness is relatively low, and it is prone to bending deformation and transverse vibration. Among the three vibration forms of saw blade, the amplitude of transverse vibration [12] is far greater than that of radial vibration and torsional vibration. Therefore, transverse vibration is the main vibration form that leads to the failure of diamond circular saw blades.

The thickness of the diamond circular saw blade is much smaller than the diameter, so the diamond circular saw blade can be simplified as a thin plate. In the process of studying the transverse vibration of diamond, which based on Kirchhoff's simplified theory of bending thin plate with small deflection. The noise of diamond circular saw blade is steady-state and wide-band noise. Therefore, this study used A weighted sound pressure level to evaluate the noise.

3.2. The analysis about noise of diamond circular saw blade
In the experiment, TEC—1352H noise meter is used to measure noise. There are two ways of frequency weighting characteristics: A and C, the measurement accuracy is ± 1.5 dB, and the resolution is 0.1 dB. When measuring, the sound level meter was fixed on the tripod, and the microphone was 30 mm away from the surface of the cutting machine. In the process of measurement, the sampling interval was 1 second, and the slow gear was used for measurement, and the average reading was taken.

![TEC—1352H sound level meter](image)

Figure 1. TEC—1352H sound level meter.

This noise experiment is carried out on QHC40 infrared bridge cutting machine. The saw blade consists of matrix and teeth, the material of the matrix is steel, and the teeth is made of diamond. The influence of different factors on the noise of diamond circular saw blade is studied in the following three aspects:
1. three kinds of stones, Lan-xing granite, Hei-jinsha granite and Mi-huang marble, were cut to study the influence of cutting materials on saw blade noise;
2. taking cutting marble as an example, the influence of cutting parameters on saw blade noise was studied by changing its rotation speed, feed speed and cutting depth and measuring noise;
3. by measuring the idling noise of diamond circular saw blades with diameters of 350 mm, 400 mm and 500 mm at different rotating speeds, the influence of the diameter of circular saw blades on noise was studied.

According to all the factors that may affect the noise of diamond circular saw blades, an orthogonal experiment with seven factors and two levels is designed to study the contribution of blade speed, feed speed, cutting depth, blade diameter, matrix thickness, segment number and friction coefficient with cutting material to noise. The experimental data shown in table 1 are finally obtained, MATLAB was used to fit eight groups of experimental data.

### Table 1. Data of seven factors two levels orthogonal experiment.

| Test No. | Rotation speed V (r/min) | Feed rate F (mm/r) | Cutting depth h (mm) | Blade diameter D (mm) | Matrix thickness L (mm) | Friction coefficient u | Segment number n | Noise dB |
|----------|--------------------------|--------------------|---------------------|----------------------|------------------------|----------------------|-----------------|---------|
| 1        | 300                      | 30                 | 5                   | 400                  | 3                      | 0.7                  | 20              | 30.76   |
| 2        | 300                      | 30                 | 5                   | 500                  | 4                      | 1.2                  | 24              | 34.91   |
| 3        | 300                      | 45                 | 10                  | 400                  | 3                      | 1.2                  | 24              | 38.62   |
| 4        | 300                      | 45                 | 10                  | 500                  | 4                      | 0.7                  | 20              | 39.44   |
| 5        | 800                      | 30                 | 10                  | 400                  | 4                      | 0.7                  | 24              | 42.53   |
| 6        | 800                      | 30                 | 10                  | 500                  | 3                      | 1.2                  | 20              | 53.86   |
| 7        | 800                      | 45                 | 5                   | 400                  | 4                      | 1.2                  | 20              | 45.2    |
| 8        | 800                      | 45                 | 5                   | 500                  | 3                      | 0.7                  | 24              | 48.08   |

The empirical formula of cutting noise is obtained as follows:

$$y = 5.381 + 0.02297x_1 + 0.154667x_2 + 0.775x_3 + 0.04795x_4 - 2.31x_5 + 5.98x_6 + 0.32x_7$$  \(1\)

Where \(x_1\) is rotation speed, \(x_2\) is feed speed, \(x_3\) is cutting depth, \(x_4\) is blade’s diameter, \(x_5\) is matrix thickness, \(x_6\) is friction coefficient, \(x_7\) is segment number.

According to the empirical formula, it can be seen that increasing the thickness of the diamond circular saw blade can reduce the noise of the saw blade to a certain extent. The other six factors, i.e., saw blade speed, feed speed, cutting depth, saw blade diameter, segment number and friction coefficient with cutting material, will increase the noise in varying degrees.

Therefore, under the circumstance of satisfying cutting conditions, the noise can be reduced to a certain extent by selecting a lesser cutting depth, feed rate and rotating speed and a thicker saw blade. As for the cutting speed, relatively low cutting speed can be selected for low-speed cutting, and when cutting at medium and high speed, the highest noise speed point should be avoided (460 m/min in this experiment).

### 3.3. The analysis about vibration modal test analysis

Modal experiment was carried out on a diamond circular saw blade with a diameter of 500 mm, and the natural frequency and main mode shape of the saw blade were measured, thus the vibration characteristics of the saw blade were analyzed. In this experiment, the pulse excitation method was used, which applied exciting force to circular saw blade first, and then measured vibration. The force hammer with force sensor could send out exciting force, and the vibration measurement signal can be received by the sensor magnetically attracted on the circular saw blade. The measured signal was transformed by
FFT in the analyzer, and the modal parameters could be obtained according to the solved frequency response function. The specific model of the equipment is shown in table 2. The flange plate fixes the circular saw blade through the central hole, and the saw blade fixing mode and the saw blade grid division are shown as in figure 2.

![Figure 2. Saw fixation and Meshing of diamond circular saw blades.](image)

**Table 2. Information of modal test equipment.**

| Instrument       | Instrument model         | Manufacturer                                      | Effect                                |
|------------------|--------------------------|---------------------------------------------------|---------------------------------------|
| Hammer           | FC43                     | Donghua dynamic testing company                   | Generating an excitation signal       |
| Force sensor     |                          | Donghua dynamic testing company                   | Picking the force signals             |
| Acceleration     | CQV9345                  | —                                                 | Picking vibration signals             |
| sensor           |                          |                                                   |                                       |
| Charge regulator | DH5857                   | —                                                 | Piezoelectric sensor signal transmission |
| Dynamic test     |                          | —                                                 | Collecting and analyzing signals      |
| analyzer         |                          |                                                   |                                       |
| Analysis software| 4633 dynamic signal test and analysis system | Donghua dynamic test technology co. ltd | Experimental modal analysis         |

The measured transverse vibration frequency of diamond circular saw blade with engineering value is mainly concentrated in low frequency band, so this study focuses on the low-order vibration frequency of diamond circular saw blade. According to the sampling theorem, the analysis frequency is between 0 and 1000 Hz, and the sampling frequency is between 0 and 2560 Hz.

After sampling, use modal analysis software to import the measured frequency response function into it. The superposition curve of frequency response function is shown in figure 3.
The frequency, damping ratio and modal shape of diamond circular saw blade can be obtained by searching the accumulated peak value of frequency response function with double cursor method. The natural frequencies and damping ratios of various modes of diamond circular saw blades are shown in table 3, and the modal shapes of various modes are shown in figure 4.

Table 3. Main modes of experimental modes of φ500 mm diamond saw blade.

| Modes | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-------|------|------|------|------|------|------|------|------|------|------|
| Frequency/Hz | 35   | 57.5 | 67.5 | 152.5| 285  | 312.5| 357.5| 445  | 565  | 614  |
| Damping ratio | 6.85 | 8.13 | 8.83 | 4.16 | 2.55 | 6.09 | 1.75 | 2.41 | 2.22 | 6.85 |

When the diamond circular saw blade works, its segments are impacted by the workpiece, and because the saw blade keeps rotating, the impact becomes periodic vibration excitation. When the excitation frequency is close to or equal to the natural frequency of the diamond circular saw blade, the saw blade will resonate. Diamond circular saw blade has a wide resonance frequency band, and has obvious resonance frequency in low frequency band, so it is easy to produce large vibration when working at this resonance frequency.

When resonance occurs, the amplitude of the saw blade increases, the vibration becomes more severe, and the damage to its matrix is greater. The red part in the figure represents the position on the saw blade with strong vibration and larger amplitude.
It can be seen from table 3 that the natural frequency of the diamond circular saw blade in the first three stages is not high, and the vibration frequency increases obviously with the increase of the order from the sixth stage. The frequencies of the first, second and third order modes are low and increase slowly, which indicates that the diamond saw blade only slightly swung in the first three orders. It can also be seen that there are many bends from the 6th order, in which the natural frequencies of 6th and 7th order, 8th and 9th order are similar, which can be regarded as the multiple roots of the solution of vibration equation. The 8th and 9th orders belong to the edge vibration, while the 6th and 7th orders belong to the internal vibration of the matrix. In practice, the impact of external factors on the saw blade should be avoided or reduced as much as possible to ensure that the deformation of the saw blade is small. Then the relationship between the working speed of the diamond circular saw blade and its excitation frequency was compared.

If n is used as the rotation speed of saw blade, z is the number of segments, the excitation frequency \( f = \frac{nz}{60} \) that can cause resonance. The higher the frequency, the higher the working speed of the diamond circular saw blade, and the greater the cutting force produced in this process, which is the
easiest to damage the saw blade. In this study, we didn't consider high-order frequencies. When the excitation frequency generated by the outside is close to the natural frequency, resonance is most likely to occur, and resonance will seriously affect the service life of the diamond circular saw blade. Therefore, in practical use, we should try our best to choose the working rotation speed with different external load excitation frequency and natural frequency to avoid the resonance of the saw blade.

According to the above analysis, by changing the diameter of diamond circular saw blade, the number of teeth and the thickness of matrix, the stiffness of circular saw blade can be improved, so as to achieve the purpose of vibration reduction and noise reduction. The experimental results can make preparations for the comparison of vibration characteristics of diamond circular saw blades before and after optimization.

3.4. Optimization design
With the medium strength topology optimization method of ANSYS Workbench, the deformation energy of the structure can be reduced under the condition of satisfying the structural constraints. Taking the maximum stiffness as the goal, the topology optimization of diamond circular saw blade was carried out. In the topology optimization design, it is not necessary to give the definition of parameters and optimization variables, as long as the parameters of the structure and the percentage of materials that can be omitted are given, the parameters and design variables are predefined by the software.

The analysis used three-dimensional SOLID95 solid elements, each of which has 20 nodes. The unit length of grid was 1 mm. The optimized area was the whole diamond circular saw blade matrix. Full restraint was imposed on the central hole of the blade at the flange, limiting the degrees of freedom in six directions. The force of 100 N is arranged on three adjacent saw teeth in the circumferential direction of the saw blade, which can simulate the force situation of the saw blade at a certain moment.

Through topology optimization of diamond circular saw blade with diameter of 500 mm, the saw blade has 24 segments, and every three adjacent segments can be divided into eight groups. After optimizing each group of segments, the optimized result picture shown in figure 5 was finally obtained.

The matrix material of diamond circular saw blade is 65Mn, and the material of segments are Cu+Co+Ni alloy.

![Figure 5. The positions of the holes.](image)

It can be found from figure 5 that there are many materials reserved in places where loads were applied. On the whole, the transmission route of force is obvious, but when we look at the local structure carefully, a small quantity of materials is reserved in some places, but these materials are not connected with the surrounding materials, so we need to make some improvements in the manufacturing process of places similar to these details.

As topology optimization is a conceptual design and belongs to the theoretical stage, its results can provide us with a reference for structural optimization, but in order to design the final product, it needs to be determined according to the actual situation. According to the results of ANSYS topology optimization, combined with the actual shape, service performance, installation and convenience of the saw blade, considering the stability of the saw blade when rotating at high speed, and considering the
overall stiffness and integrity of the actual saw blade, only part of the area is designated as the location for opening vibration and noise reduction holes, so the designed opening positions are at the four positions which are shown as figure 5. At the same time, in order to avoid stress concentration and fracture of collective materials, the holes were rounded. The saw blade matrix was processed according to the position in the figure by high-pressure water cutting machine, and the vibration and noise reduction saw blade is obtained.

4. Comparison of diamond circular saw blade before and after optimization

According to the topology optimization results, the position of the hole on the substrate of the diamond circular saw blade can be determined, and the noise and vibration characteristics of the diamond circular saw blade before and after optimization were compared by measuring the vibration and noise reduction of the diamond circular saw blade as below.

4.1. Comparison of noise before and after optimization

According to the noise value of the pre-optimized diamond circular saw blade at each rotating speed, under the same conditions, the noise value of the optimized diamond circular saw blade was obtained by the same method. The experimental data are shown in table 4.

| Rotation speed/(r/mm) | 150 | 300 | 450 | 600 | 800 |
|-----------------------|-----|-----|-----|-----|-----|
| Before optimization/(A)| 68.95 | 73.88 | 78.56 | 77.11 | 79.62 |
| After optimization/(A) | 66.13 | 70.52 | 75.46 | 73.24 | 75.74 |

It can be seen from table 4 that when idling, the noise of the optimized diamond circular saw blade will gradually increase with the increase of cutting speed, but at the same speed, the noise value of the optimized saw blade is generally lower than that of the pre-optimized saw blade. In this experiment, the noise of the optimized saw blade can be reduced by 4.8% maximally.

4.2. Comparison of vibration characteristics before and after optimization

The modal test of the optimized diamond circular saw blade is carried out. The result data of diamond circular saw blades before and after optimization are shown in table 5, from which we can see the contrast relationship between natural frequencies of saw blades before and after optimization.

| Order number | 1st | 2nd | 3rd | 4th | 5th | 6th |
|--------------|-----|-----|-----|-----|-----|-----|
| Before optimization/Hz | 35 | 57.5 | 67.5 | 152.5 | 285 | 312.5 |
| After optimization/Hz | 32.7 | 58 | 70.6 | 161.8 | 291.3 | 326 |
| Order number | 7th | 8th | 9th | 10th | 11th | 12th |
| Before optimization/Hz | 357.5 | 445 | 565 | 614 | 643 | 694 |
| After optimization/Hz | 374.3 | 489.8 | 583.5 | 659.4 | 684.5 | 718.7 |

Table 5 shows the comparison of natural frequencies of saw blades before and after optimization. The natural frequencies of diamond circular saw blades before and after optimization are not much different in the first order, but they are obviously different from the second order. The natural frequency of circular saw blades with holes tends to increase. The higher the order, the more obvious the difference
in natural frequency. From the 9th order, although the natural frequency of the optimized saw blade is still higher than that of the pre-optimized saw blade, the increasing trend has declined. Therefore, according to the topology optimization method described in this paper, determining the position and shape of the hole in the diamond circular saw blade matrix can indeed increase the natural frequency within a certain range of order, thus improving the stability of the saw blade and reducing the vibration and noise.

5. Conclusions
In this study, the noise and vibration characteristics of diamond circular saw blade were analyzed, and based on the analysis results, the corresponding measures to reduce noise and vibration were put forward. Using the topology optimization function of ANSYS Workbench, the topology optimization of diamond circular saw blades with no holes in the matrix was carried out, and the noise and natural frequency value of diamond circular saw blades before and after optimization were measured and compared again.

The test results showed that the noise of the optimized saw blade can be reduced by 4.8%, and the natural frequencies of the first 12 orders were increased in varying degrees, which proves that the vibration and noise of the saw blade were reduced after optimization. Therefore, it is proved that the optimization method described in this paper has guiding significance for the actual processing in factories.

References
[1] Marin J 1998 Ind. Diamond Rev. 58 (577) 34
[2] Ersoy A and Atici U 2004 Diam. Relat. Mater. 31 223-7
[3] Wei X, Wang C and Zhou Z 2010 J Mater. Process. Tech. 139 (3) 227-280
[4] Kvietkova M, Gaff M and Gasparik M 2015 BioResources 10 (1) 1657-66
[5] Davim J, Reis P, Maranhao C, Jackson M, Cabral G and Gracio J 2010 Int. J. Mater. Prod. Tec. 37 (1) 46-50
[6] Zhao M 2009 Processing Tools and Technology of Stone (Beijing: Publishing House of Electronics Industry)
[7] Xie J and Tamaki J 2007 J Mater. Process Tech. 5 (186) 253-8
[8] Meng Y, Wei J, Wei J, Chen H and Gui Y 2019 Comput. Electron. Agr. 157 38-48
[9] Li S, Wang C, Zheng L and Wang Y 2016 J Mater. Process Tech. 238 108-123
[10] Yong C, Hang Z and Wang J 2019 Eur. J. Mech-A-Solid 75 197-204
[11] Yurdakul M and Akdas H 2012 Int. J. Rock Mech. Min. 53 38-44
[12] Shang X and Su J 2006 ANSYS/LS-DYNA Method and Engineering Example of Dynamic Analysis (Beijing: China Water&Power Press)