2018

Stress Analysis Of Key Components And Vibration Property Research Of The Meshing Pair In Single Screw Compressors

Chengyu Peng
Xi'an Jiaotong University, China, People's Republic of, zgcypeng@163.com

Zhao Zhang
Xi'an Jiaotong University, China, People's Republic of, 13259978235@163.com

Pankang Xiong
Xi'an Jiaotong University, China, People's Republic of, 454538214@qq.com

Lei Liu
Xi'an Jiaotong University, China, People's Republic of, liulei0019940308@163.com

Quanke Feng
Xi'an Jiaotong University, China, People's Republic of

See next page for additional authors

Authors
Chengyu Peng, Zhao Zhang, Pankang Xiong, Lei Liu, Quanke Feng, and Weifeng Wu

Research on Vibration Characteristics of Meshing Pair in Single Screw Compressors

Chengyu PENG, Zhao ZHANG, Pankang XIONG, Lei LIU, Quanke FENG*, Weifeng WU

School of Energy and Power, Xi'an Jiaotong University
Xi'an 710049, China

* Corresponding Author: Quanke Feng*
Tel(Fax):+86-029-82663783 Email: qkfeng@mail.xjtu.edu.cn

ABSTRACT

The single screw compressor is a kind of rotary compressor with excellent performance, and has a series of advantages, such as simple structures, remarkable mechanical balance, high volume efficiency, large machine capacity, and etc, all of which allow for promising application prospects of it in areas such as air compression, refrigeration, waste heat recovery and other fields. The screw and star wheel in a single screw compressor play a key role in the performance of the compressor, and their dynamic characteristics affect the vibration characteristics of the single screw compressor and the attrition rate of the star wheel directly.
In this paper, a 3-D geometric model of meshing pair of the single screw compressor was established. And modal mode analysis of screw and star wheel was conducted with the help of ANSYS Workbench R16.1 finite element analysis simulation platform. The vibration characteristics of screw and star wheel were predicted by solving their respective natural frequency, critical speed and so on. It was found that great significance does exist between inherent frequency of screw rotor and excitation frequency it stirred and no potential trouble of resonance was found. The natural frequencies of star wheel varied greatly with materials. And resonance of the cast iron star wheel occurred in a relatively scare chance.

1. INTRODUCTION

Since invented by Zimmen in the 1960s, the single screw compressor had greatly attracted people's attention because of its advantages such as simple structures, few parts, excellent dynamic balance, low noise and high reliability (Zimmen, 1972). However, the development in single screw compressor was relatively slow due to the high abrasion of meshing pair. In recent years, with the application of PEEK material, abrasion resistance of meshing pair was improved to some extent, but it does not solve the abrasion problem of meshing pair fundamentally.
According to the hydrodynamic lubrication theory, the abrasion resistance of meshing pair can be improved when a lubricant film is formed between the star gear teeth and the spiral groove (Jin, 1982). For this reason, some researchers have proposed the linear envelope profile, which is widely used in the single screw compressor in the market at present, should be replaced with the linear quadratic envelope and the cylindrical quadratic envelope (Jin and Tang, 1985).Multi-linear (Feng and Guo, 2005)and multi-cylindrical enveloped meshing pair lines (Wu and Feng, 2007) published recently are expected to greatly improve the abrasion resistance of meshing pair, but these profiles are still under research.
In addition to the improvement of meshing pair profiles, some researchers have studied the effects of star wheel dynamics and machining accuracy on the abrasion properties of meshing pairs and pointed out that low machining accuracy is the main cause of meshing pair rapid abrasion. However, the improvement of machining accuracy in recent years has not changed the current situation of meshing pair rapid abrasion fundamentally. Later, through observation and investigation of a large number of failed star wheels, scholars found that the abrasion of the front side of the star gear teeth was greater than that on the rear side, and that the front tooth surface would even be damaged completely sometimes, and that there were obvious bright traces of the contact between the star wheel and the star wheel frame.

The analysis revealed that the vibration in the meshing pairs and the interaction between the star wheel and the support during the operation of the compressor may cause more thorough damage to the intersecting edges between front teeth and the upper surface of the star wheel. Accordingly, it is necessary to establish further dynamic models of screw rotor and star wheel rotor, and to analyze the dynamics of the meshing pair system.

2. Theoretical Basis of Modal Analysis

Since the screw and star wheel belong to rotating machinery, it particularly refers to the modal analysis of rotor dynamics here.
Modal analysis is a technique for calculating the natural vibration characteristics of a structure, which can be used to compute the vibration characteristics of the structure (including natural equality, mode shape and modal participation factor). The BLOCK LANCZOS method is used in the modal analysis of screw and star wheel, and the equation of motion (Genta G, 2007) is as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\} \tag{1}$$

Where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{\ddot{x}\}$ is the generalized acceleration, $\{\dot{x}\}$ is the generalized velocity, $\{x\}$ is the generalized displacement, $\{F\}$ is the external load.
When the external load of the system is zero, it means $\{F\}=0$, and then the equation becomes:

$$[M]\{\ddot{x}\}+[K]\{x\}=0 \quad \text{OR} \quad [M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=0 \tag{2}$$

The modal analysis is to use the free vibration equation to solve the natural frequencies and corresponding modes of the structure. The solution of the hypothetical formula is:

$$\{x\}=\{\Phi\}e^{\omega t} \quad \text{OR} \quad \{x\}=\{\Phi\}\sin(\omega t+\varphi) \tag{3}$$

Where $\{\Phi\}$ is the Amplitude array, ω is the Harmonic vibration frequency, t is the time variable, φ is the phase position.
Then introduce formula (3) into formula (2) and eliminate the factor $e^{\omega t}$, obtain the basic equation of eigenvalue and eigenvector solved by undamped modal analysis.

$$\{[K]\text{-}\omega_i^2[M]\}\{\Phi_i\}=0 \tag{4}$$

Where $\{\Phi_i\}$ is the mode vector of the I-order mode, ω_i is the natural frequency of the I-order mode
Φ and ω can be determined by solving the above equations. ω_1、ω_2、…、ω_n represent natural frequencies ($0 \le \omega_1 < \omega_2 < ... < \omega_n$), Φ_1、Φ_2、…、Φ_n represent the modes of natural frequencies.

3. Research on Vibration Characteristics of Meshing Pair

The screw rotor of single screw compressor may vibrate strongly due to the action of periodic dynamic load, and the increasingly sharp dynamic stress leads to premature fatigue failure. Meanwhile, the influence of vibration on the service life of the star wheel subjected to impact load can never be underestimated. Therefore, it is necessary to study and analyze them from the aspect of dynamics.
In this paper, the Workbench Mechanical dynamic rotor analysis module is used to analyze the modes of screw and star wheel and compute its natural frequency and critical speed, which is eventually meant to optimize the structural design and avoid the frequency range of resonance.
The parameters of single screw compressor studied in this paper are shown in Table 1.

Table 1: Compressor parameters

Screw's diameter D_1/mm	Screw's length L/mm	Star wheel's diameter D_2/mm	Centre to Centre spacing A/mm	Star wheel tooth's width B/mm

310	280	340	248	49

3.1 Research on Vibration characteristics of Screw rotor

Single screw compressor is driven and powered by motor through coupling and screw rotor shaft, through which the motor provides a simulated vibration for the screw rotor system. In order to avoid resonance, it is necessary to analyze the modal vibration of the screw rotor and determine its natural frequency and mode shape.

The assembly of screw rotor system is imported into the Modal module of ANSYS Workbench, and the boundary condition is defined as Figure 1. The two rings are the journal of bearing constraint.

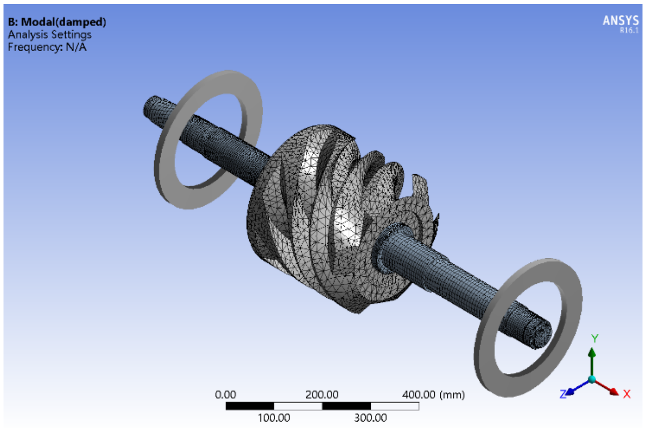


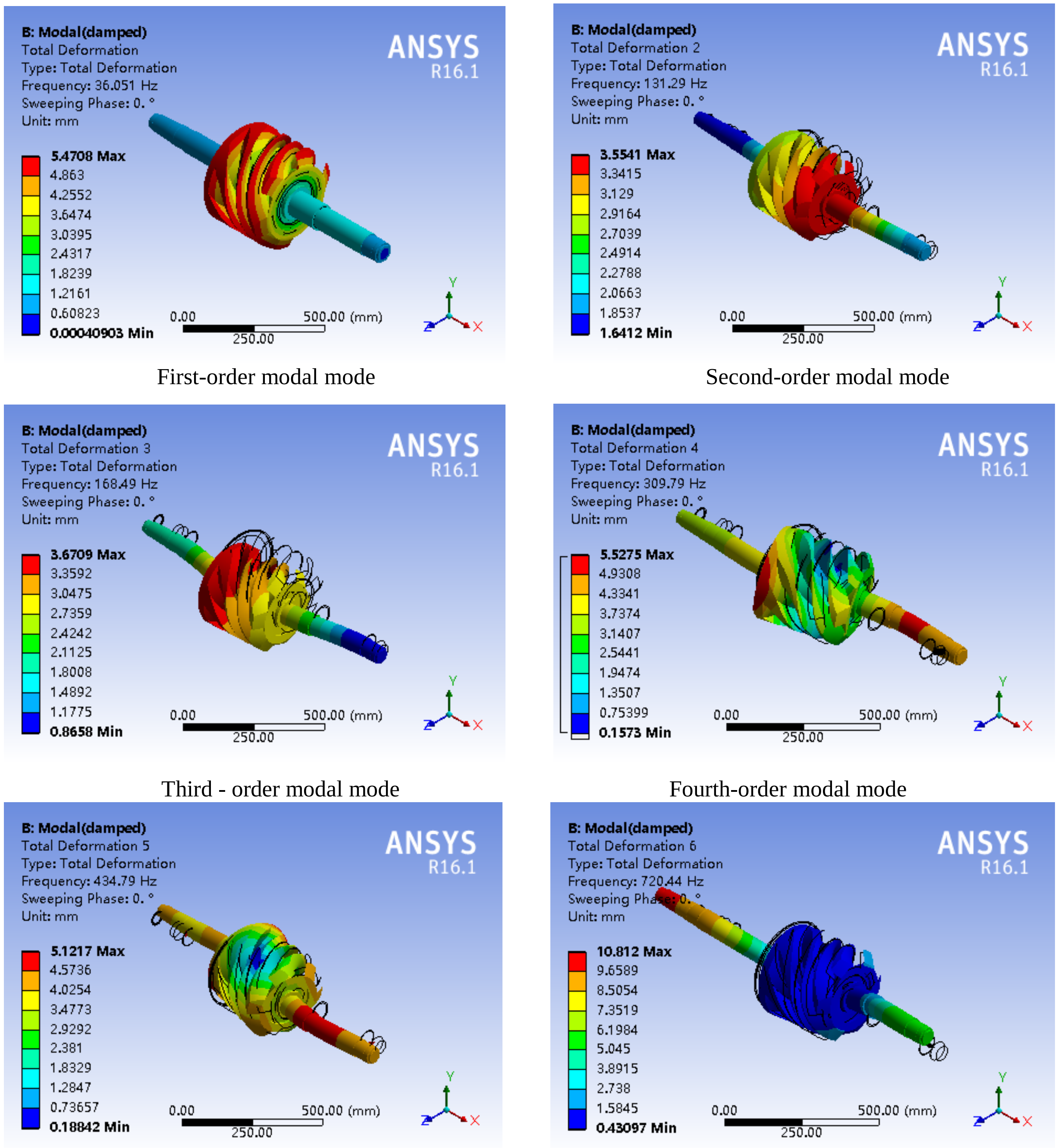
Figure 1: Model of Screw Assembly

The damping condition should be considered in the analysis and timing of the solver. The Damped option of the bearing is chosen. The mode extraction method is automatically selected by the program and the first 6 modes are also extracted. The Coriolis effects is turned on in the rotor dynamics control option, and so is the Campbell diagram. The first 6 order natural frequencies obtained are shown in Table 2.

Table 2: The first 6 order natural frequencies / Hz

order	natural frequencies / Hz
1	36.05
2	131.29
3	168.49
4	309.79
5	434.79
6	720.44

In order to make it more obvious and convenient to compare the modal mode, the deformation magnification factor is adjusted appropriately and the three-dimensional wire-block diagram in static state is displayed as a reference. The results are as follow:



First-order modal mode

Second-order modal mode

Third - order modal mode

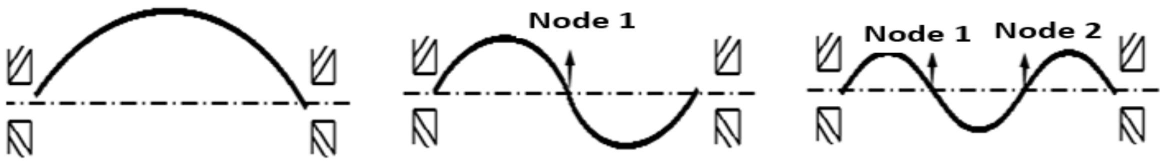
Fourth-order modal mode

Fifth- order modal mode

Sixth-order modal mode

Figure 2: The first 6 modes of screw rotor

According to the modal mode, we can conclude the following statement:
1) The first order is the vortex mode (circumferential rotating vibration) and it is accompanied by the expansion deformation of the rotor.
2) The second and third order is the main vibration of radial vibration, but merely the direction of vibration is changed, and the second order is in vertical direction and the third is in horizontal direction.
3) The fourth and fifth order is the main vibration with node number 1, and the vibration direction is nearly vertical.
4) The sixth order is the main vibration, in which the number of nodes is 2.
As shown in Figure 3, in order to see the vibration curves of each mode more clearly, the first order mode is a vortex mode, and the non-axial vibration mode curve of the screw system is a straight line.



a) 2nd/3rd order mode curve b) 4th/5th order mode curve c) 6th order mode curve

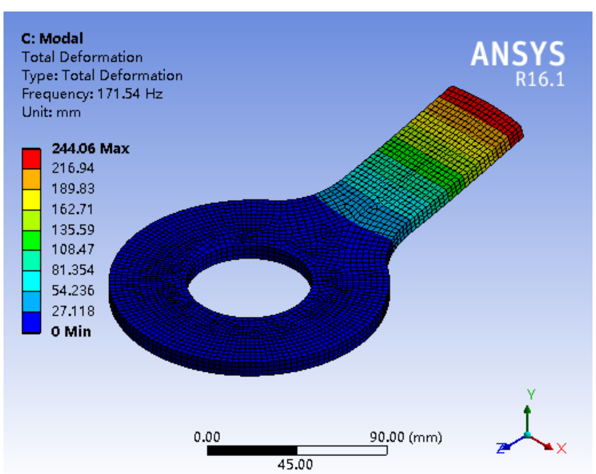
Figure 3: Each order mode simplified curve

3.2 Research on Vibration Characteristics of Star Wheel

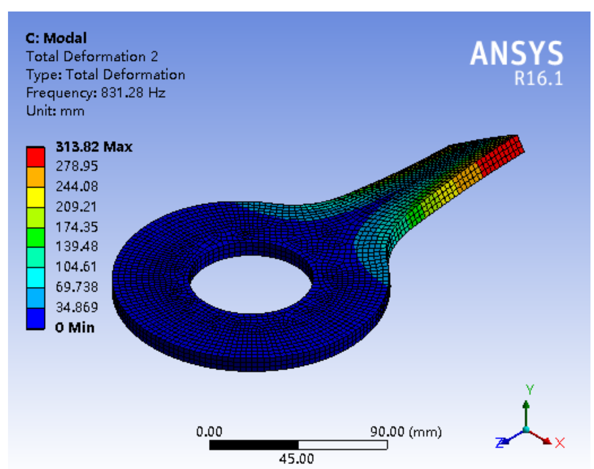
In order to study the inherent vibration characteristics of the star wheel itself, the first 6 natural frequencies and the corresponding modal modes of the star wheel are extracted by using BLOCK LANCZOS method. Since the 11 teeth of the star wheel are exactly the same, only one tooth should be analyzed. The vibration modes of each order are shown in Table 3and Figure 4 respectively.

Table 3: The first 6 natural frequencies of star rings

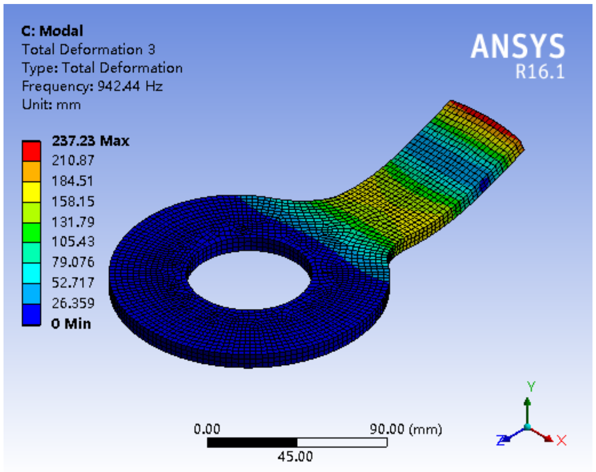
order	natural frequencies /Hz	Critical speed / r·min^{-1}
1	171.54	10292.4
2	831.28	49876.8
3	942.44	56546.4
4	1104.4	66264
5	1882	112920
6	1893.6	113616



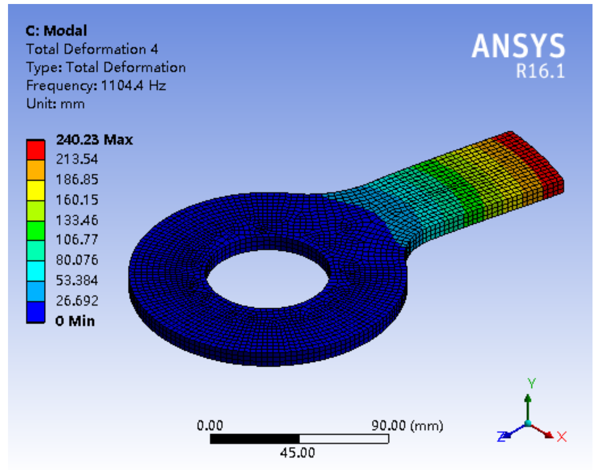
First-order modal mode



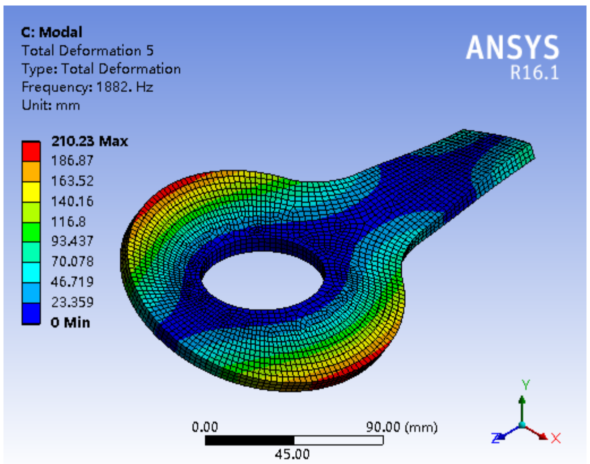
Second-order modal mode



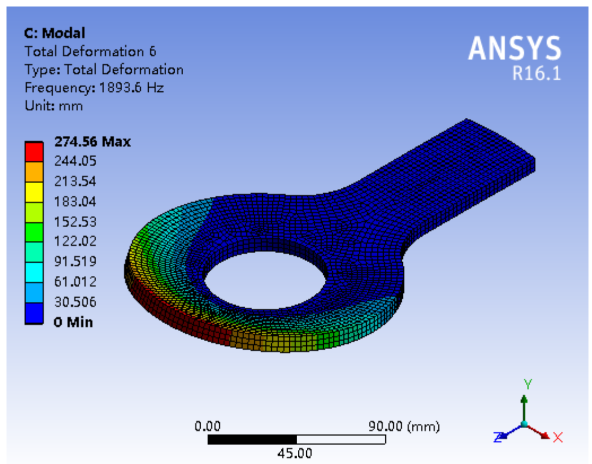
Third - order modal mode



Fourth-order modal mode



Fifth- order modal mode



Sixth-order modal mode

Figure 4: The first 6 modes of star wheel

It can be concluded from the calculation results that

1) The first order vibration mode is the vibration of the star tooth up and down in the direction perpendicular to the plane of the star wheel.
2) The second order form is the torsional vibration of the star wheel.
3) The third order is the bending vibration of the star tooth up and down.
4) The fourth order is the lateral bending vibration of the star tooth.
5) The fifth, and the sixth order is the root torsion.

4. Results and Analysis

The natural vibration characteristics of the screw rotor are obtained by analyzing the natural frequency and modal mode. It is necessary to compare and analyze the external excitation and its own characteristics.

In general, the single screw compressor is driven by a motor with a speed of 2970 r·min^{-1}, so the frequency of the fundamental frequency excitation is 49.5Hz and the 2 frequency doubling excitation is 99.0Hz. The frequency of the other frequency doubling excitation can be calculated in turn, and that is:

$$F_n = n \cdot f_0 , \quad (n = 1, 2, 3, \ldots) \tag{5}$$

Where f_0 is the motor excitation fundamental frequency, F_n is the screw rotor stimulated by motor frequency. According to the vibration mechanics, the fundamental frequency and the frequency doubling of the excitation should avoid the natural frequency of the structure if possible. It is usually stipulated that there is a hidden danger of resonance when the excitation frequency is 0.8 to 1.2 times of the inherent frequency of the structure. By comparing

the excitation frequencies with the natural frequencies of Table 2, it is found that the 3 frequency doubling of the excitation is within the second order modal vibration frequency range of the structure, and the 9 frequency doubling and 10 frequency doubling are in the fifth order modal vibration frequency range of the structure.
However, the comparison of the resonance frequency with the previous 2 order natural frequencies can meet the requirements, because the high order frequency doubling intensity is very low and can often be ignored. By comparison, it is found that the difference between the two is huge, and there is no hidden danger of resonance, but it is still advised that more attention should be paid to compressor to make sure no abnormal vibration in the start - up stage occurs.
In the same way, the natural vibration characteristics of the star wheel are obtained by solving the natural frequency and modal mode. It is necessary to compare and analyze the external excitation and its own characteristics obtained above. The rated speed of the screw is 3000 r·min^{-1}, the number of screw cogging is 6, and the number of teeth of the star wheel is 11, and the rated speed of the star wheel is:

$$n_2 = n_1 \cdot {}^{Z_1}\!/_{Z_2} \tag{6}$$

Where n_1 is the rated speed of screw, Z_1 is the number of screw cogging and Z_2 is the number of teeth of star wheel.
Therefore, the rated speed of the star wheel is 1620 r·min^{-1}. This speed is much lower than the critical speed of each stage, which can be seen from table 3-3, and can avoid resonance. All mentioned above is mainly for the modal analysis of the PEEK material wheel. In fact, the star wheel may also be made of cast iron, stainless steel and other materials. Here is a comparison of the modal results of the same star wheel using PEEK material and cast iron. As shown in Figure 4-1, it can be seen that the natural frequency ratio of the metal material like cast iron is much higher than that of the star wheel, like PEEK. So the possibility of resonance is lower at a non-high speed (less than10000 r·min^{-1}).

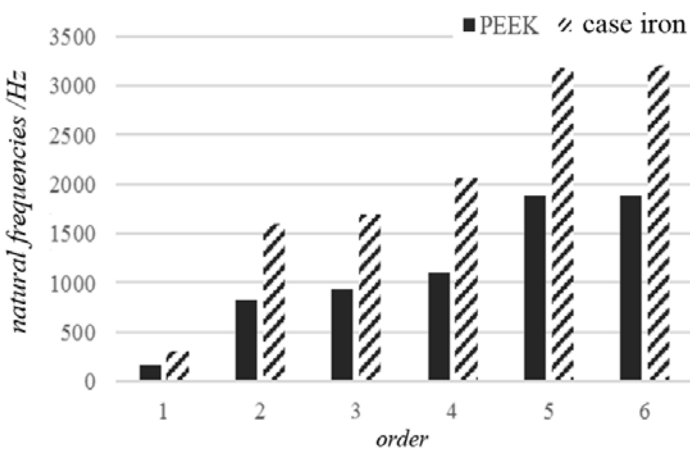


Figure 5: Natural frequency of star wheel under different material conditions

5. Conclusion

In this paper, a three-dimensional geometric model is established for the meshing accessory components of a single screw compressor, and the modal analysis is conducted on the screw and the star wheel with the help of ANSYS Workbench finite element analysis simulation platform, and the natural frequency and critical speed are solved.
The calculation results show that the critical speed of the 1 order natural frequency of the screw rotor is found to be 2163 r·min^{-1}, and the actual rotating speed of the screw rotor is 2970 r·min^{-1}, so the difference between them is huge and there is no hidden danger of resonance. Meanwhile, for the frequency conversion single screw compressor, 2163 r·min^{-1} should be avoided and it is also necessary to pay attention to see whether abnormal vibration occurs in the stage of starting and stopping.
According to the modal analysis of the star wheel, it is found that the rated rotational speed of the star wheel using PEEK material is 1620 r·min^{-1}, which is much lower than the critical speed of each order and can guarantee no resonance occurs. However, the natural frequency of the metal star wheel like cast iron is much higher than that of a PEEK star wheel. For this reason, the possibility of resonance is lower at a non - high speed.

NOMENCLATURE

M	Mass	(kg)
C	Damping	(N·s/m)
K	Stiffness	(N/m)
x	Displacement	(m)

REFERENCES

Zimmern B., Patel G. J. (1972). Design and operating characteristics of the zimmern single screw compressor, in: Proceedings of the 1972 Purdue Compressor technology Conference, West Lafayette, USA, pp. 96-99.

Jin G. (1982) Study on profile and hydrodynamic lubrication of single screw compressor. Journal of Xi'an Jiaotong University, 16: 75-82.

Jin G &Tang Y (1985). New Progress in the study of meshing pair profile of single Screw Compressor. Journal of Xi'an Jiaotong University, 1915: 1-9.

Feng, Q, Guo B, & Zhao C, et al. (2005). Design method for meshing pair of single screw compressor with multiple linear envelopes. Compressor technology, 191 (3): 1 -6.

Wu W, Feng Q, &Xu J. (2007). Principle of Multi-Cylindrical Envelope for Tooth profile of single Screw Compressor. Journal of Xi'an Jiaotong University, Vol41: 11.

Genta G. (2007). Dynamics of rotating systems. Springer Science & Business Media.