Modal Analysis of Cylindrical Gear Based on Finite Element Model

Shiwei Niu

***Abstract*— In order to analysis the factors of influencing cylindrical gears natural frequency, and improve the dynamic characteristics of gear. 3D finite element model of cylindrical gear was established. Natural frequency and vibration model of the gear were studied. Effects of material and structure on the natural frequency were discussed. The results show that structure of the gear is one of the factors to influence the natural frequency. The method can be used to gear parameter design, theoretical analysis and provides reference basis for the dynamic optimization of gear.**

***Index Terms*—cylindrical gear, finite element method, modal analysis, natural frequency.**

I. Introduction

Cylindrical gear transmission is the most common type of transmission mechanism in modern machinery, which is widely used in various kinds of gear reducer, machine tools and transmission gear box[1]. Its transmission ratio is stable, the transmission efficiency is high, the work reliability is high. But if the gear structure design is not reasonable, it will affect its dynamic performance, in the work process will produce a large vibration and noise, but also affect the accuracy and reliability of the work. Modal analysis technology has become an important method in the analysis and design of vibration system[3]. It is a modern method to study the dynamic characteristics of structure, and it is the application of system identification method in the field of engineering vibration. The mode is the natural vibration characteristic of the mechanical structure, each mode has the special natural frequency, the damping ratio and the modal vibration mode. In the transmission of movement and power, the transmission system is transmitted to the gear system through various external and internal excitation, which causes the gear to produce vibration during the transmission. The natural frequency of the gear is one of the dynamic characteristics of gear, the generation and transmission of dynamic load and vibration form of the system has very important influence [3], so the analysis of the dynamic characteristics of the gear, the gear design and improvement and the whole transmission system of the improvement of the dynamic performance of the important practical significance.

In this paper, a solid model of cylindrical gear is established by using Pro/E software and is imported into finite element analysis software, in order to do modal analysis of gear. Through the establishment of the model of three kinds of materials, the influence of material properties on the natural frequency of gear is analyzed. The effect of different structures on the frequency of the gears is analyzed when the gear structure is improved.

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II. Modal Analysis Foundation

In this paper, a solid model of cylindrical gear is established by using Pro/E software and is imported into finite element analysis software, in order to do modal analysis of gear. Through the establishment of the model of three kinds of materials, the influence of material properties on the natural frequency of gear is analyzed. The effect of different structures on the frequency of the gears is analyzed when the gear structure is improved.

Gear system can be achieved by the finite element theory of elastic mechanics, the motion differential equations as follows [4]:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \tag{1}$$

[*M*], [*C*] and [*K*] are the gear mass matrix, damping matrix and stiffness matrix, respectively.

$\{\ddot{X}\}$, $\{\dot{X}\}$ and $\{X\}$ are the gear vibration acceleration vector, the velocity vector and displacement vector, respectively.

$\{F(t)\}$ is gear suffered external exciting force vector.

$$\{X\}=\{x_1, x_2, \cdots, x_n\}^T \tag{2}$$

$$\{F(t)\}=\{f_1, f_2, \cdots, f_n\}^T \tag{3}$$

The system of free vibration equation is obtained without external force, namely $\{F(t)\}=0$. The damping effects on them is not big when solve the natural frequencies and natural modes of the gear. Therefore, the damping can omit and the equation of motion for undamped free vibration is,

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}=0 \tag{4}$$

Its corresponding eigenvalue equation is,

$$([K]-\omega_i[M])\{X_i\}=0 \tag{5}$$

Where, ω_i is the *i* order natural frequency of the modal.

Free vibration of multi degree of freedom system can be decomposed into n single degree of freedom of harmonic vibration superposition, or that the system is a linear combination of the free vibration of n intrinsic mode vibration.

III. Finite Element Model

Fig.1 shows the geometric model of the gear. Fig.2 shows the finite element model.

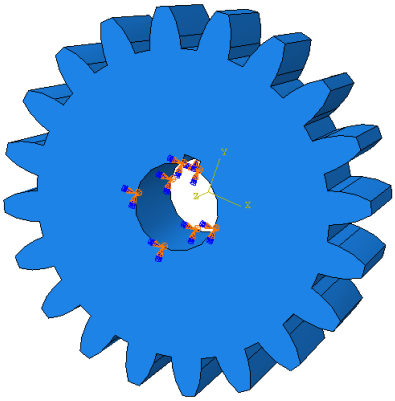

Fig.1 geometric model of the gear

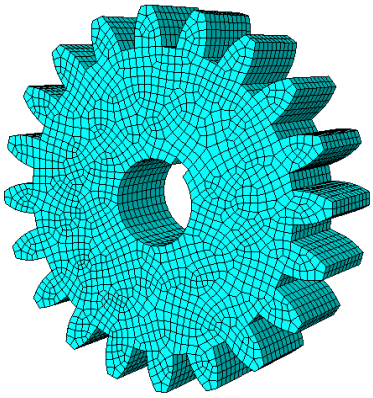

Fig.2 Finite element model of the gear

The gear basic parameters of the gear such as shown in Table 1. Three different materials were analyzed in this paper and the material physical parameters as shown in Table 2.

Table 1 Basic parameters of the gear (mm)

Name	Equations	Value
Pitch circle diameter	$d = mz$	80
Tooth addendum	$h_a = h_a^* m$	4
Tooth dedendum	$h_f = (h_f^* + c^*)m$	5
Addendum circle diameter	$d_a = (2h_a^* + z)m$	88
Tooth root circle diameter	$d_f = (z - 2h_a^* - 2c^*)m$	70
Base circle diameter	$d_b = d\cos a$	75.2
Base circle pitch	$P_b = p\cos a$	11.8
Tooth thickness	B	20

Table 2 Material parameters

Materials	Elasticity Modulus [MPa]	Poisson's ratio	Density [kg/m^3]
Cast iron	1.6e5	0.286	7800
40Cr	2.1e5	0.278	7840
20CrMo	2.11e5	0.277	7870

IV. Simulation Results

Fig.3 shows the first 9 order vibration modes of the gear with 40Cr. The first-order vibration is circumferential, axially substantially no vibration, the end surface of the circumferential direction of vibration. The 2, 3, 7, 8 order are bending vibration, mainly gear bending vibration. The fourth order is umbrella and axial vibration is umbrella mode. The 5,6 order are fold vibration show mainly axial appears regular waves vibration mode, the end face appears regular polygonal vibration mode, combination of structure distortion of folded. The 9 order is radial vibration, main show is gear along the radial expansion, end face appears polygon mode, axially substantially has no vibration.

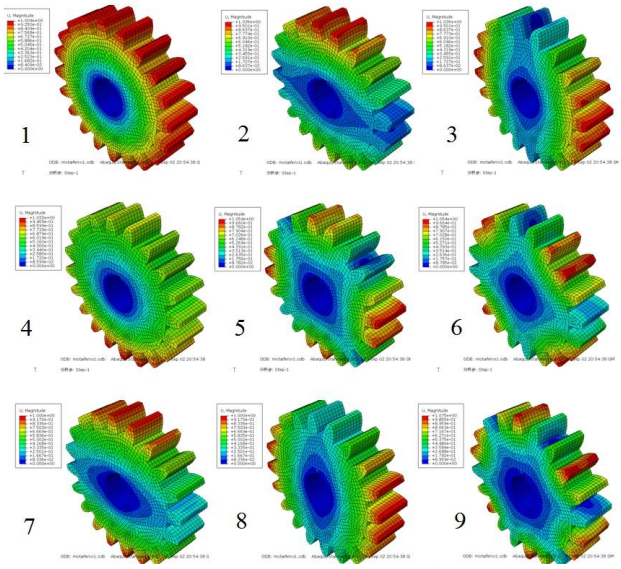

Fig.3 The first 9 order vibration modes

Table 3 shows the natural frequencies of the gear. Because the material 40Cr and 20CrMo have the similar elastic modulus, therefore, the figure of two curves basically overlap. Under the condition of the same order, there is a certain relationship between the natural frequency and material of the gear. The greater the elastic modulus of materials, in the same order, the greater the natural frequency of the gear, In the same order number under the working frequency of the gear, the smaller the probability of the work of the noise is small, thus increases the transfer efficiency, prolong the working life.

Table 3 The first 9 order natural frequency

Order	Cast iron	40Cr	20CrMo
1	8.3520	9.5725	9.5805
2	9.6089	10.978	10.982
3	9.8375	11.238	11.243
4	11.061	12.658	12.622
5	12.517	14.338	14.349
6	12.547	14.373	14.384
7	17.425	19.953	19.967
8	17.566	20.115	20.129
9	20.061	22.989	23.008

V. Modal Analysis of Gear with Web Type

In order to study the influence of gear structure on natural frequency, the original gear is processed web-type and the gear basic parameters remain the same, as shown in Fig.4. The first 9 natural frequencies are extracted from the analysis results of three kinds of materials gears, as shown in Table 4. Fig.5 shows the first 9 vibration modes of cast iron gears.

By comparison, the frequencies of the improved web type gear is smaller than solid type structures, it shows the structure of gear is related with the natural frequency. So in the parametric design of gear, the natural frequencies of the gear can be changed by changing the structure of the gear without strength decrease, avoid resonance occurs at work to decrease the noise of generation and improve the transmission efficiency of gear. All orders are changed by comparing the all orders of gear vibration mode and initial mode, the improved web type gear occurs more torsional vibration and bending vibration, and large deformation.

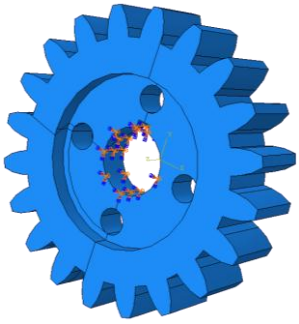

Fig.4 The gear with web type

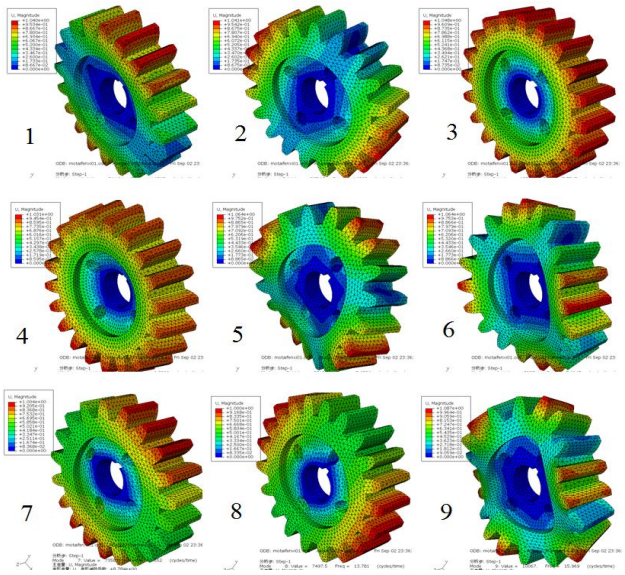

Fig.5 The first 9 order vibration modes of sternum gear

Table 4 The first 9 order natural frequency of web type gear

Order	Cast iron	40Cr	20CrMo
1	4.6263	5.2822	5.2842
2	4.6868	5.3514	5.3534
3	5.7842	6.6252	6.6302
4	6.2299	7.1123	7.1148
5	7.6536	8.7594	8.7652
6	7.6947	8.8031	8.8085
7	13.652	15.618	15.627
8	13.781	15.766	15.775
9	15.969	18.280	18.293

VI. Conclusion

Modal analysis of cylindrical gears are done through the finite element software, and the cylindrical gears have different materials and different structure. The natural frequencies of gear is related to the materials. The greater the elastic modulus of materials, the greater the natural frequency of the gear. The natural frequencies of gear is related to the structure, and the natural frequency of the gear can be changed because of the changing of the structure. In the first 9 order modes of gear, there are 5 kinds of modes. The weak link of the gears can be known through the vibration mode diagram.Using the finite element software to carry on the modal analysis to the gear, it can provide the basis for the gear design and the theory research, and provides the reference for the staff to carry on the gear maintenance.

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