Modal analysis and optimization of typical parts of 2K-V reducer

Abstract: As a new type of high-precision gear transmission mechanism, The transmission accuracy of the 2K-V reducer will be greatly affected by vibration. With the RV110E reducer as the research object, a three-dimensional model of the needle wheel is established.Using the finite element analysis software, the natural frequency and mode shape of the needle wheel under the output condition are calculated, and compared with the calculated gear meshing frequency.It is found that under the working condition of the needle wheel, the vibration frequency is within the gear meshing frequency range, which is easy to cause resonance, and affects the transmission precision of the whole machine;The part of the outer shell of the needle wheel and the oil seal of the skeleton is the weakest and prone to deformation;By adding 6 reinforcing ribs between the needle wheel flange and the outer casing, and increasing the flange outer diameter by increasing the flange outer diameter, the natural frequency can be increased, and the deformation concentrated region can be transferred to the outer casing and the reinforcing rib. The connected parts avoid resonance and increase the service life of the needle wheel.

Key words:2K-V reducer;the needle wheel;Modal analysis;The optimization design

2K-V (called Rotary Vector, RV for short) is a new planetary transmission mechanism composed of 2K-H planetary transmission and K-H-V planetary transmission.It is a new type of planetary gear transmission mechanism with small tooth difference. The structure adopts the combination of involute gear planetary transmission and cycloidal pinion planetary transmission. It has compact structure, small volume, light weight, transmission precision and transmission, High efficiency, large transmission ratio range, etc[1].Due to its excellent performance, 2K-V reducer has been used more and more in industrial robots, CNC machine tools, printing machinery, semiconductor equipment, radar and other precision machines and fields.

At present, Japan's research on 2K-V reducer has reached the international leading level,The 2K-V reducer produced by ourselves often has problems such as insufficient transmission precision and large vibration in the application,To this end, a large number of research conducted by researchers in various universities and research institutions in China.It can be seen from the related literature that there are few studies on the inherent characteristics of the needle wheel.As a very important part of the 2K-V type reducer, the needle wheel case supports and protects the components of the internal cycloidal wheel, planetary gear, crankshaft, input and output flange, and pin gear during the output of the planet carrier. Secondly, when fixing the planet carrier, the needle wheel can be used as an output tool to realize the normal operation of the reducer.Because the different working states have different constraints on the needle wheel, and the inherent characteristics of the object are closely related to the constraints of the object, but in the case where the needle wheel is fixed, it will not resonate with the whole machine.Therefore, in this paper, with the RV110E reducer as the model, by establishing the finite element model of the needle wheel, only the modal of the needle wheel as the output condition is analyzed, and the natural frequencies and modes of each order are obtained respectively. Analyze its intrinsic characteristics, and then give an optimization scheme to lay the foundation for subsequent kinematics and dynamics analysis.

1. 2K-V type reducer transmission principle

The schematic diagram of the transmission system of the 2K-V type reducer is shown in Figure 1. It is mainly composed of main components such as cycloidal gear, crank shaft, planetary gear, planet carrier, the needle wheel and sun gear. The second speed reduction mechanism, wherein the first stage speed reduction mechanism is an involute cylindrical gear planetary speed reduction mechanism, and the second stage speed reduction mechanism is a cycloidal pin wheel planetary speed reduction mechanism [2, 3].

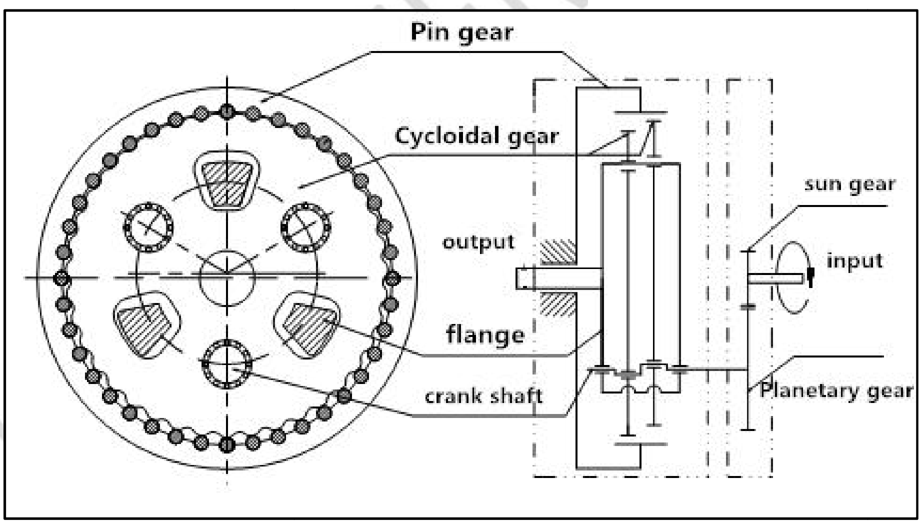

FIG.1 schematic diagram of transmission system of 2K-V type reducer

When fixing the planet carrier and the needle wheel as an output,At this time, the transmission ratio of the system i_Z is

$$i_Z = -\frac{Z_p}{Z_s}\frac{Z_r}{Z_r - Z_b} \tag{1}$$

In the formula Z_s——the number of Sun gear ;

Z_p——the number of planetary gear ;

Z_b——the number of cycloid gear ;

Z_r——the number of Pin gear , In general $Z_r = Z_b + 1$ 。

In this output mode, the power is input from the input shaft, transmitted to the planetary gear via the sun gear, and the crank shaft is rotated to complete the first-stage deceleration.In the second-stage deceleration, the rotation of the planetary gear acts as the power input for the rotation of the cycloidal wheel. The rolling bearing on the crank shaft drives the cycloidal wheel to perform the eccentric revolution movement opposite to the power input. The eccentric revolution movement of the cycloidal wheel can pass through the needle. The tooth completes the gearless gear transmission to realize the output of the pin gear housing. At this time, the input and output rotation directions are opposite.And this can also be obtained by equation (1).

2. Basic principle of modal analysis

Modal refers to the natural vibration characteristics of various mechanical structures. Each mode of each object has its specific natural frequency, mode shape and damping ratio [4]. Modal analysis is to decompose the complex vibration of a specific structure. As individual vibrations, we can determine the vibration characteristics of the structural system through modal analysis, and provide a basis for subsequent kinematics and dynamics analysis.

The modality is an intrinsic property of the object itself. It is only related to the shape, material properties, and constraint characteristics of the structure. It is independent of other conditions, so we can simplify the complex dynamic equation to equation (2).

$$[M]\{\ddot{u}\} + [K]\{u\} = 0 \tag{2}$$

In the formula $[M]$——Structure mass matrix；

$[K]$——Structural stiffness matrix；

$\{\ddot{u}\}$——Nodal acceleration vector；

$\{u\}$——Nodal displacement vector。

When harmonic vibration occurs, then $u = U\sin(\omega t)$ the equation can be converted to equation (3).

$$[K] - \omega_i^2 [M]\{\varphi_i\} = 0 \qquad (3)$$

From formula (3), the vibration frequency ω_i and mode of the vibration structure of each order φ_i can be obtained [5].

Through modal analysis, we can understand the vibration of the structure under certain constraints, compare it with the simulation model established by the computer, and prove whether the established model is correct, and determine that the subsequent mechanical analysis can be continued.

3. Modal analysis of the needle wheel

3.1 Establishment of a three-dimensional model

Use solidworks 2016 to create a 3D model of the needle wheel. To make it easier to follow up and change the 3D model, use the “Equation” function in the “Tools” function to define the basic parameters, array features, and stretch features of each sketch. Etc. When the model changes are needed, the corresponding parameters can be changed directly in the equation, and the control global variables can be selected to achieve rapid change of the model and achieve more efficient work efficiency. The automatically generated needle wheel simulation model is shown in Figure 3, It is convenient to import the created 3D model into the Workbench working environment and store the model as a file in the "x_t" format.

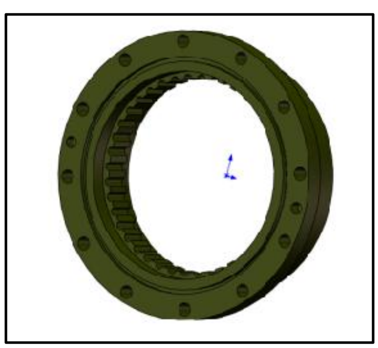

FIG. 2 simulation model of the needle wheel

3.2 Add material properties.

This article uses the RV110E reducer as a model.The material defining the needle wheel is QT450-10. QT450-10 is a ductile iron with good plasticity and toughness, good weldability and machinability, and is often used in the manufacture of wheels for automobiles and tractors. , clutch housing, reducer housing, etc., its material properties are shown in Table 1.

Table 1 QT450-10 material properties

project name	Modulus of elasticity (GPa)	density (kg/ m^3)	Poisson's ratio
QT450-10	169	7060	0.257

In the Workbench working environment, after importing the previously stored "x_t" needle wheel file, define the material properties of the QT450-10 in the Engineering Data function, as shown in Figure 3, and enter the modal analysis environment.

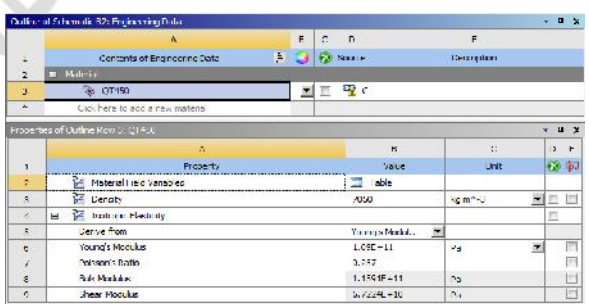

FIG. 3 defines the material properties of QT450-10

3.3 Meshing

In order to better reflect the real situation of the model, the chamfering and rounding of the model are not simplified in the processing of the model. In the meshing, the tetrahedral mesh is selected, and the chamfer and the joint are meshed. The encrypted form, through meshing, has a total of 103,339 nodes and 65,896 cells, as shown in Figure 4 and Figure 5.

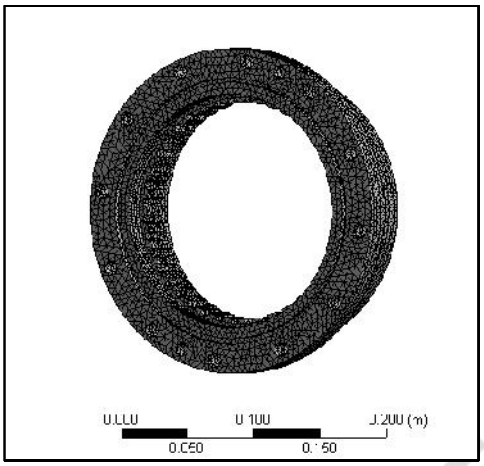

FIG. 4 Overall meshing

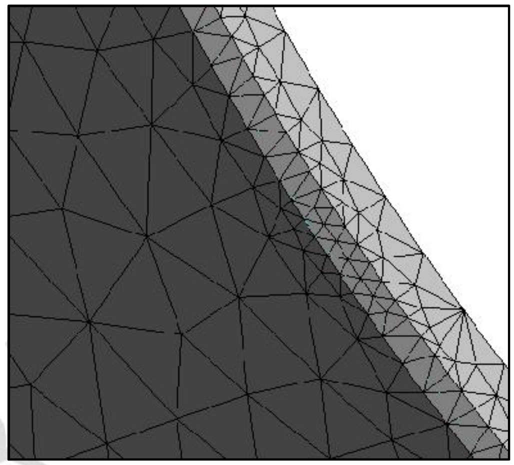

FIG. 5 Meshing at the chamfer

3.4 Constraint form

The difference of the constraint forms will lead to different modal analysis results. The constraint form of the needle wheel is divided into two types [6]. In this paper, only the constraint form of the needle wheel output is considered, that is, the needle wheel is used as the output. Not only must it be fixed by the needle sheath, but also subject to bearing constraints.

3.5 Modal analysis

After the modal analysis of ANSYS Workbench, the first 10 natural frequencies and modes of the needle wheel are obtained. As shown in Table 2, each mechanical structure has multiple different natural frequencies under certain constraints, but generally only the minimum natural frequency is concerned, because at this natural frequency, the structure is most prone to resonance, and the mode of the minimum vibration frequency is shown in Figure 6.

Table 2 Natural frequency and mode shape of the needle wheel output

Order number	frequency/Hz	Vibration mode
1	0	Rotate around the Z axis
2	1384.4	Telescopic along the XOY plane
3	1587.9	Telescopic along the XOY plane
4	1661.9	Bending around the Z axis
5	1669.3	Bending around the Z axis
6	1917.1	Telescopic along the XOY plane
7	1917.5	Telescopic along the XOY plane
8	4077.2	Distorted along the XOY face
9	4085.1	Distorted along the XOY face
10	4332.1	Distorted along the XOY face

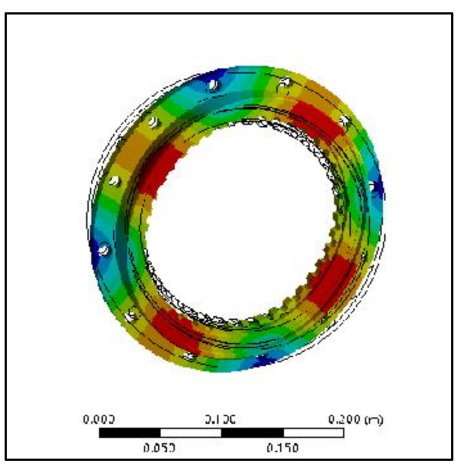

FIG. 6 Mode shape of the needle wheel output

4. Modal result analysis

When the needle wheel is used as the output, it can be obtained from the formation pattern. The deformation of the needle wheel is not only concentrated on the XOY surface expansion and deformation, and the linear addition of the various modes is fitted to the actual situation of the needle wheel output. Out is the overall telescopic deformation, not the area.

In the 2K-V type reducer, there are gears of the first-stage transmission and the second-stage transmission in the transmission process. There is a meshing frequency. The calculation formula of the first-stage meshing frequency f_{m1} and the second-stage meshing frequency f_{m2} is derived as an equation (4) and (5).

$$f_{m2} = Z_b \bullet Z_r \bullet f_{out} \tag{4}$$

$$f_{m2} = Z_b \bullet Z_r \bullet f_{out} \tag{5}$$

In the formula，f_{out}——output speed（r/s），

It can be calculated that the first stage meshing frequency and the second stage meshing frequency are 1466.66 Hz and 1430 Hz, respectively.

Comparing the minimum natural frequency of the needle wheel with 1384.4Hz and the natural meshing frequency of the first stage transmission of 1466.66Hz, it can be seen that the natural frequency of the needle wheel is within the range of gear meshing frequency, so it is easy to generate resonance and affect the transmission precision of the whole transmission system. In order to avoid this, it is necessary to optimize the needle wheel.

5. the needle wheel optimization

In order to avoid the lack of transmission accuracy caused by the natural frequency of the needle wheel and the resonance phenomenon of the whole machine, the optimization design of the needle wheel should be considered. According to the basic principle of modal analysis, the modality is the inherent property of the structure, only with The material of the machine component, the constraint mode and the shape are related. For the 2K-V type reducer, the transmission form is determined, so the constraint mode for the needle wheel case is also fixed, so It is necessary to make appropriate improvements to its structural form [7].

It can be seen from the modal analysis structure that the maximum deformation of the needle wheel occurs in the joint between the shell and the skeleton oil seal, so it should be considered to strengthen this part of the structure.

Since the 2K-V type reducer has a very tight structure, there is no space for the inner cavity of the needle wheel for us to change the structure.Therefore, it is possible to add 6 reinforcing ribs on the outer side of the needle wheel, and the edge radius of the appropriate pin-toothed bosses to generate a new needle wheel model is shown in Figure 7.Adding the rib and increasing its thickness can improve its stability. The calculation results are shown in Table 3. From the results, the natural frequency of the needle wheel is increased from 1384.4 Hz to 1664.4 Hz,increased by 20%, the natural frequency comparison before and after optimization is shown in Figure 8. It is far from the first-stage gear meshing frequency, which can better avoid the resonance phenomenon caused by frequency coincidence.

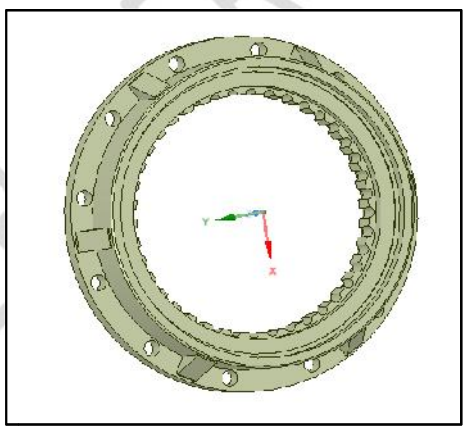

FIG. 7 3D model after modification

Table 3 natural frequencies and modes of the pin gear shell output after changing the form

Order number	frequency/Hz	Vibration mode
1	0	Rotate around the Z axis
2	1664.4	Telescopic along the XOY plane
3	1668.3	Telescopic along the XOY plane
4	1903.1	Bending around the Z axis
5	1910.4	Bending around the Z axis
6	2950.4	Telescopic along the XOY plane
7	2950.8	Telescopic along the XOY plane
8	4258.3	Distorted along the XOY face
9	4412.3	Distorted along the XOY face
10	4709.9	Distorted along the XOY face

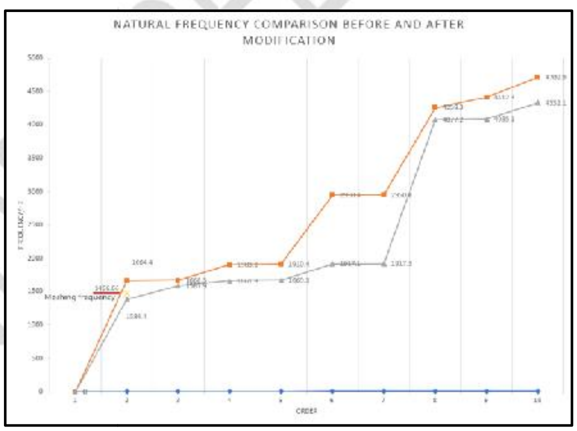

FIG. 8 Natural frequency comparison chart before and after optimization

The optimized vibration pattern is shown in Figure 9. It can be seen that after changing the shape and optimizing the needle wheel, not only the natural frequency is increased, but also the place where the deformation is concentrated is transferred from the weak part of the skeleton oil seal link. The outer shell of the needle wheel and the part connecting the reinforcing ribs improve the stability of the needle wheel and increase the service life of the whole machine.

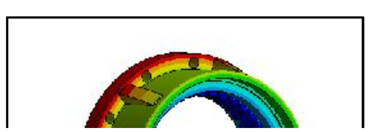

FIG. 9 vibration mode of the needle wheel after modification

6. Conclusion

（1）Taking the RV110E reducer as a model, the natural frequency of the needle wheel is analyzed, and compared with the gear meshing frequency of the whole machine。It is easy to cause the resonance between the needle wheel and the whole machine under the output condition of the needle wheel.

（2）Through the various modes of the needle wheel, it is found that the part of the outer shell of the needle wheel and the skeleton oil seal is weak, and it is easy to be deformed. The optimization of this part should be considered in consideration of optimization.

（3）As can be seen from the vibration mode of the needle wheel optimized by changing the structural form, the deformation concentration position is changed and transferred to the part where the outer shell of the needle wheel is connected with the stiffener.This method can improve the stability of the needle housing and increase the service life of the machine.

Reference

[1]S L Pan,C Wang. Volume calculation of RV reducer[J]. IOP Conference Series: Materials Science and Engineering,2019,504(1).

[2]Hongji Li,Geng Hou,Weidong He,Yinghui Zhang. Simulation and analysis of contact state between cycloid gear and pin wheels in RV reducer[J]. Journal of Physics: Conference Series,2018,1074(1).

[3]Li Lixing, He Weidong and Wang Xiuqi 1999 The Study on High-accuracy RV Drive Used in Robot [J].Journal of Dalian Railway Institue Vol.20, No.2 pp.1-11

[4]Ayoub Mbarek,Alfonso Fernández Del Rincon,Ahmed Hammami,Miguel Iglesias,Fakher Chaari,Fernando Viadero,Mohamed Haddar. Comparison of experimental and operational modal analysis on a back to back planetary gear[J]. Mechanism and Machine Theory,2018,124.

[5]Poi Voon Er,Kok Kiong Tan. Machine Vibration Analysis based on Experimental Modal Analysis with Radial Basis Functions[J]. Measurement,2018.

[6]R. Durand,B.G. Pantoja-Rosero,V. Oliveira. A general mesh smoothing method for finite elements[J]. Finite Elements in Analysis & Design,2019,158.

[7]Romain Mesnil,Cyril Douthe,Christiane Richter,Olivier Baverel. Fabrication-aware shape parametrisation for the structural optimisation of shell structures[J]. Engineering Structures,2018,176.