Journal of Scientific Research & Reports

23(6): 1-9, 2019; Article no.JSRR.49706
ISSN: 2320-0227

Modal Analysis and Optimization of Typical Parts of 2K-V Reducer

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Authors' contributions

This work was carried out in collaboration among all authors. Author CC designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors LH and WJ managed the analyses of the study. Author ZW managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2019/v23i630137
Editor(s):
(1) Dr. Angela Gorgoglione, Department of Civil and Environmental Engineering, University of California, Davis, USA.
Reviewers:
(1) Naga Bhushana Rao Vakada, Jawaharlal Nehru Technological University, India.
(2) Shashidhar K. Kudari, Jawaharlal Nehru Technological University University, India.
(3) Tiago Morkis Siqueira, University of São Paulo, Brazil.
Complete Peer review History: http://www.sdiarticle3.com/review-history/49706

Original Research Article

Received 16 April 2019
Accepted 23 June 2019
Published 06 July 2019

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 are calculated, when it's under the output condition, then compared with the calculated gear meshing frequency. It is found when the needle wheel is used as an output, the vibration frequency is within the gear meshing frequency range, which is easy to cause resonance, thereby 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, increasing the flange outer diameter at the same time, the natural frequency can be increased, 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.

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Keywords: 2K-V reducer; the needle wheel; modal analysis; the optimization design.

1. INTRODUCTION

2K-V (called Rotary Vector, RV for short) is a new planetary transmission mechanism, which is composed of 2K-H planetary transmission and K-H-V planetary transmission. It’s a new type of planetary gear transmission mechanism with a 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, high transmission accuracy, high efficiency and large transmission ratio range [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.

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, for this reason, a large number of researches 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 [2]. As a very important part of the 2K-V type reducer, the needle wheel case supports and protects the components of the internals during the output of the planet carrier, such as the cycloidal wheel, planetary gear, crankshaft, input and output flange, and pin gear. 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, 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, in this case, the natural frequencies and modes of each order are obtained respectively. Analyzing its intrinsic characteristics, then give an optimization scheme to lay the foundation for subsequent kinematics and dynamics analysis.

2. 2K-V TYPE REDUCER TRANSMISSION PRINCIPLE

The schematic diagram of the transmission system of the 2K-V type reducer is shown in Fig. 1. It is mainly composed of main components such as cycloidal gear, crankshaft, planetary gear, planet carrier, the needle wheel and sun gear. The transmission system uses a 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 pinwheel planetary speed reduction mechanism [3,4].

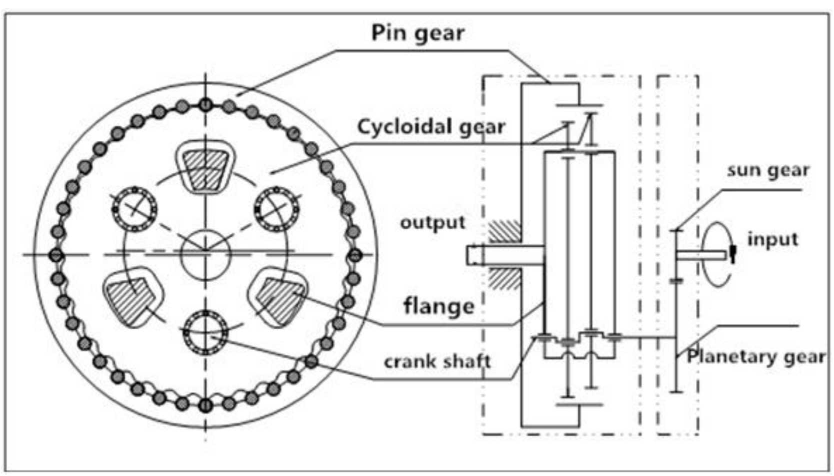


Fig. 1. Schematic diagram of the transmission system of 2K-V type reducer

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 equation

Z_s —— The number of Sun gear tooth;

Z_p — The number of planetary gear tooth;

Z_b — The number of cycloid gear tooth;

Z_r — The number of Pin gear tooth,

In general。 $Z_r = Z_b + 1$

In this output mode, the power is input from the input shaft and transmitted to the planetary gear via the sun gear, whereby the crankshaft 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 crankshaft drives the cycloidal wheel to perform the eccentric revolution movement opposite to the power input and 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).

3. THE 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 [5]. Modal analysis is to decompose the complex vibration of a specific structure into individual vibrations. The modal analysis can determine the vibration characteristics of the structural system, 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 simplify the complex dynamic equation to the undamped case as given by equation (2).

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

In the equation

$[M]$ ——Structure mass matrix;

$[K]$ ——Structural stiffness matrix;

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

$\{u\}$ ——Nodal displacement vector。

When harmonic vibration occurs, the equation (2) can be converted another equation [6], just like the equation (3).

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

From equation (3), the vibration frequency ω_i and mode of the vibration structure φ_i of each order can be obtained [7].

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

4. MODAL ANALYSIS OF THE NEEDLE WHEEL

4.1 Establishment of a Three-dimensional Model

Use Solidwork 2016 [8] 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. When the model changes are needed, the corresponding parameters can be changed directly in the equation, the control global variables can be selected to achieve the rapid change of the model and achieve more efficient work efficiency. The automatically generated needle wheel simulation model is shown in Fig. 2. The model stored as the "x_t" format in order to import into the Workbench working space easily [9].

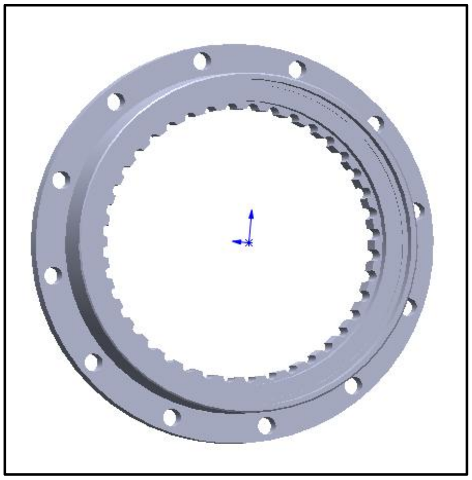


Fig. 2. Simulation model of the needle wheel

4.2 Add Material Properties

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

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 Fig. 3, and enter the modal analysis environment.

4.3 Meshing

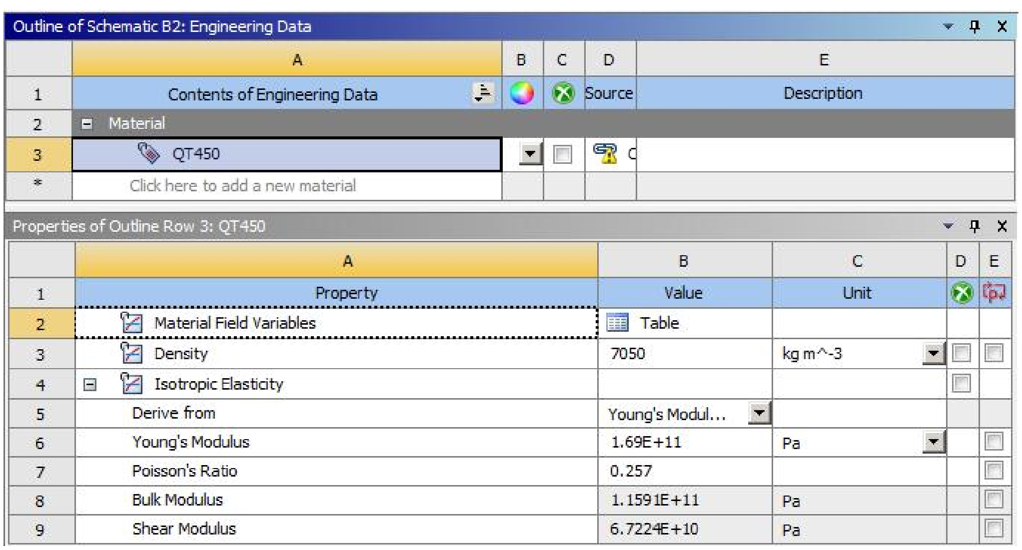
In order to reflect the real situation of the model better, the chamfering and rounding of the model are not simplified in the processing of the model. The tetrahedral meshing is selected for grid division, and the chamfer and connection are in the form of grid encryption. After grid division, a total of 103339 nodes and 65896 elements are obtained, as shown in Fig. 4 and Fig. 5.

4.4 Constraint Form

The difference between the constraint forms will lead to different modal analysis results [11]. The constraint form of the needle wheel is divided into two types and only the constraint form of the needle wheel output is considered in this paper. 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, as shown in Fig. 6.

Table 1. QT450-10 material properties

project name	Modulus of elasticity（GPa）	density（kg/m^3）	Poisson's ratio
QT450-10	169	7050	0.257



Outline of Schematic B2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data			Source	Description
2	Material				
3	QT450			C	
*	Click here to add a new material				

Properties of Outline Row 3: QT450

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	7050	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Modul...			
6	Young's Modulus	1.69E+11	Pa		
7	Poisson's Ratio	0.257			
8	Bulk Modulus	1.1591E+11	Pa		
9	Shear Modulus	6.7224E+10	Pa		

Fig. 3. Define the material properties of QT450-10

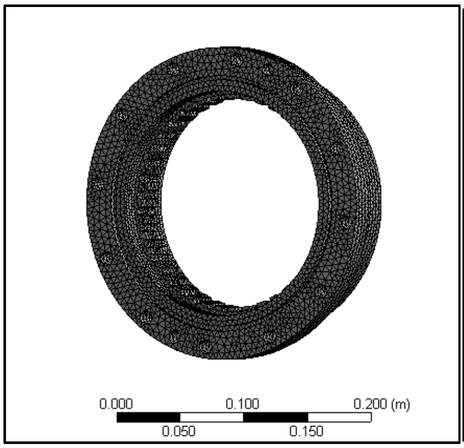


Fig. 4. Overall meshing

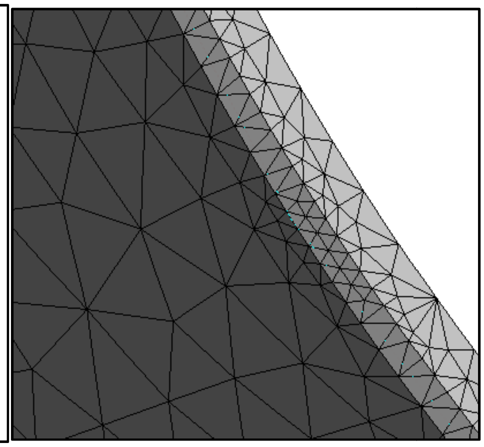


Fig. 5. Meshing at the chamfer

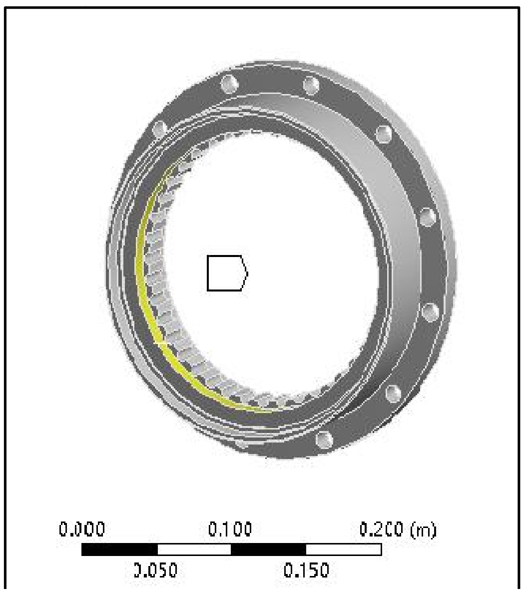


Fig. 6. Constraint form when the needle wheel is output

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

Mode 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

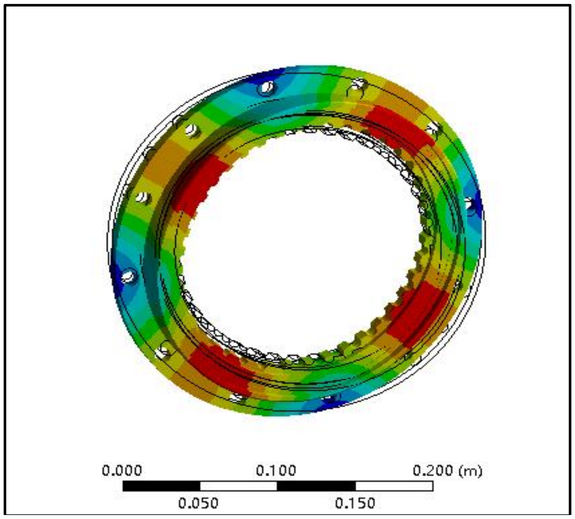


Fig. 7. Mode shape of the needle wheel output

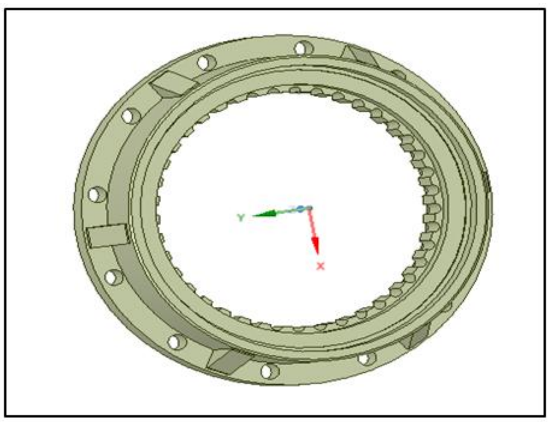


Fig. 8. 3D model after modification

4.5 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 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 Fig. 7.

5. MODAL RESULTS ANALYSIS

When the needle wheel is used as the output, available from the Vibration mode, the deformation of the needle wheel is not only concentrated on the XOY surface expansion and deformation, the linear addition of the various modes is fitted to the actual situation of the needle wheel output. It can be seen that it is the overall expansion deformation rather than the region.

In the 2K-V type reducer, there are gears of the first-stage transmission and the second-stage transmission. There are meshing frequencies. The calculation formula of the first-stage meshing frequency and the second-stage meshing frequency is derived as the equation (4) and (5).

$$f_{m1} = Z_b \bullet Z_r \bullet f_{out} \tag{4}$$

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

In the equation, f_{out}——output speed (rad/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.

6. THE NEEDLE WHEEL OPTIMIZATION

In order to avoid the lack of transmission accuracy, which is 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 is also fixed, so it is necessary to make appropriate improvements to its structural form [12].

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 so there is no space for the inner cavity of the needle wheel to change the structure. Therefore, it is possible to add 6 reinforcing ribs on the outer side of the needle wheel and increase the edge radius of the pin-toothed boss appropriately. The new needle wheel model is shown in Fig. 8. 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 Fig. 9. It is far from the first-stage gear meshing frequency, which can better avoid the resonance phenomenon caused by frequency coincidence.

The optimized vibration pattern is shown in Fig. 10. 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 skeleton oil seal link to the part of the outer shell of the needle wheel and the ribs. Improving the stability of the needle wheel and increasing the service life of the whole machine.

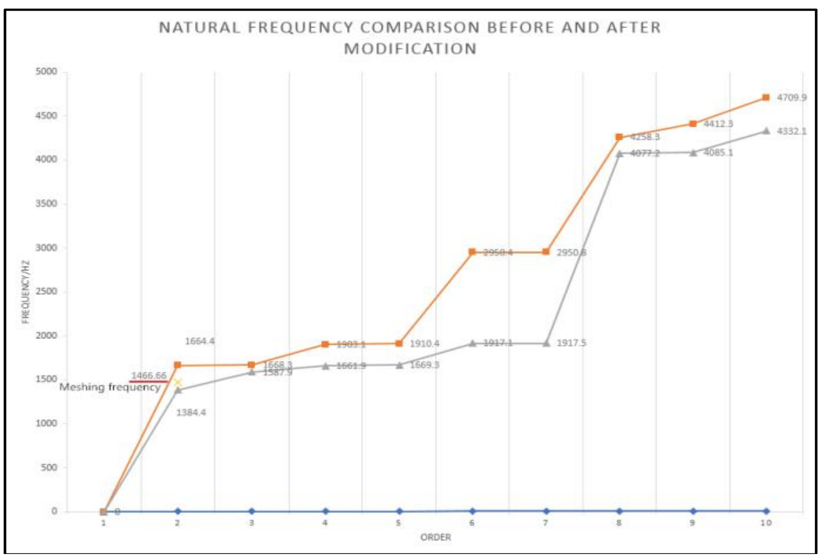


Fig. 9. Natural frequency comparison chart before and after optimization

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

Mode 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

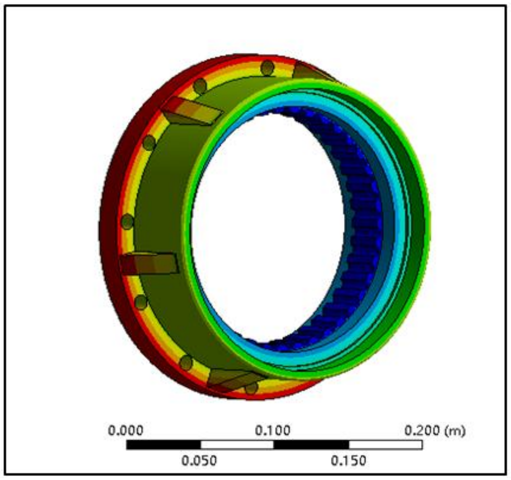


Fig. 10. Vibration mode of the needle wheel after modification

7. CONCLUSION

In conclusion it can be said that the RV110E reducer can be used as a model, the natural frequency of the needle wheel has been 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. Through the various modes of the needle wheel, it has been found that the part of the outer shell is weak, which is between the needle wheel and the skeleton oil seal, and it is easy to be deformed. The optimization of this part should be considered. 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. It is found when the needle wheel is used as an output, the vibration frequency is within the gear meshing frequency range, which is easy to cause resonance, thereby 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, increasing the flange outer diameter at the same time, the natural frequency can be increased; 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.

ACKNOWLEDGEMENT

This work was supported by 2017 Henan Province Graduate Education Innovation Medium Funding Project (2017-1).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle3.com/review-history/49706