

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

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4 **Abstract:** As a new type of high-precision gear transmission mechanism, the transmission
5 accuracy of the 2K-V reducer will be greatly affected by vibration. With the RV110E
6 reducer as the research object, a three-dimensional model of the needle wheel is
7 established. Using the finite element analysis software, the natural frequency and mode
8 shape of the needle wheel are calculated, when it's under the output condition, then
9 compared with the calculated gear meshing frequency. It is found when the needle
10 wheel is used as an output, the vibration frequency is within the gear meshing frequency
11 range, which is easy to cause resonance, thereby affects the transmission precision of the
12 whole machine. The part of the outer shell of the needle wheel and the oil seal of the
13 skeleton is the weakest and prone to deformation. By adding 6 reinforcing ribs between
14 the needle wheel flange and the outer casing, increasing the flange outer diameter at the
15 same time, the natural frequency can be increased, the deformation concentrated region
16 can be transferred to the outer casing and the reinforcing rib. The connected parts avoid
17 resonance and increase the service life of the needle wheel.

18 **Keywords:** 2K-V reducer; The needle wheel; Modal analysis; The optimization design

19 1. Introduction

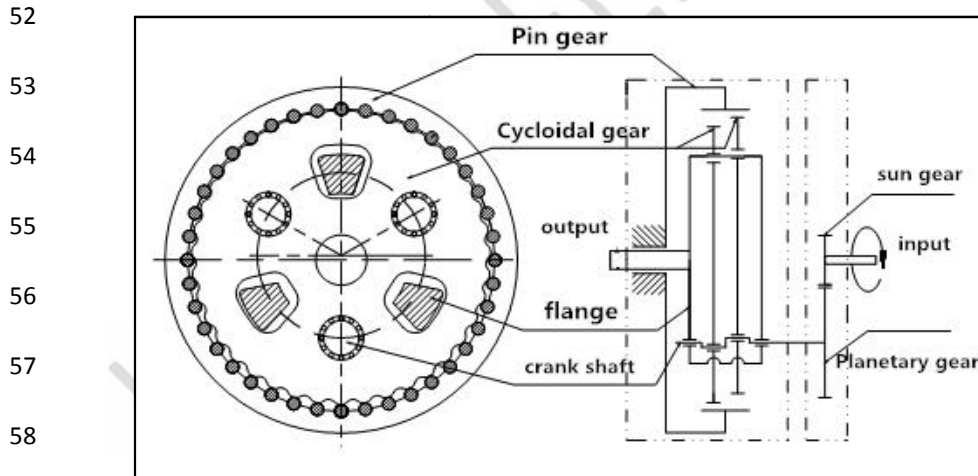
20 2K-V (called Rotary Vector, RV for short) is a new planetary transmission mechanism, which is
21 composed of 2K-H planetary transmission and K-H-V planetary transmission. It's a new type of
22 planetary gear transmission mechanism with a small tooth difference. The structure adopts the
23 combination of involute gear planetary transmission and cycloidal pinion planetary transmission.
24 It has compact structure, small volume, light weight, high transmission accuracy, high efficiency
25 and large transmission ratio range^[1]. Due to its excellent performance, 2K-V reducer has been
26 used more and more in industrial robots, CNC machine tools, printing machinery, semiconductor
27 equipment, radar and other precision machines.

28 At present, Japan's research on 2K-V reducer has reached the international leading level, the 2K-V
29 reducer produced by ourselves often has problems, such as insufficient transmission precision and
30 large vibration in the application, for this reason, a large number of researches conducted by
31 researchers in various universities and research institutions in China. It can be seen from the
32 related literature that there are few studies on the inherent characteristics of the needle wheel^[2].
33 As a very important part of the 2K-V type reducer, the needle wheel case supports and protects the

34 components of the internals during the output of the planet carrier, such as the cycloidal wheel,
 35 planetary gear, crankshaft, input and output flange, and pin gear. Secondly, when fixing the planet
 36 carrier, the needle wheel can be used as an output tool to realize the normal operation of the
 37 reducer. Because the different working states have different constraints on the needle wheel, the
 38 inherent characteristics of the object are closely related to the constraints of the object, but in the
 39 case where the needle wheel is fixed, it will not resonate with the whole machine. Therefore, in
 40 this paper, with the RV110E reducer as the model, by establishing the finite element model of the
 41 needle wheel, only the modal of the needle wheel as the output condition is analyzed, in this case,
 42 the natural frequencies and modes of each order are obtained respectively. Analyzing its intrinsic
 43 characteristics, then give an optimization scheme to lay the foundation for subsequent kinematics
 44 and dynamics analysis.

45 2. 2K-V type reducer transmission principle

46 The schematic diagram of the transmission system of the 2K-V type reducer is shown in Fig.1. It is
 47 mainly composed of main components such as cycloidal gear, crankshaft, planetary gear, planet
 48 carrier, the needle wheel and sun gear. The transmission system uses a second-speed reduction
 49 mechanism, wherein the first stage speed reduction mechanism is an involute cylindrical gear
 50 planetary speed reduction mechanism, and the second stage speed reduction mechanism is a
 51 cycloidal pinwheel planetary speed reduction mechanism [3, 4].



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

60 When fixing the planet carrier and the needle wheel as an output, at this time, the transmission
 61 ratio of the system i_z is

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$$i_z = -\frac{Z_p}{Z_s} \frac{Z_r}{Z_r - Z_b} \quad (1)$$

63 In the equation Z_s —the number of Sun gear tooth;

64 Z_p —the number of planetary gear tooth;

65 Z_b —the number of cycloid gear tooth;

66 Z_r —the number of Pin gear tooth, In general $Z_r = Z_b + 1$.

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

75 2. The basic principle of modal analysis

76 Modal refers to the natural vibration characteristics of various mechanical structures. Each mode
77 of each object has its specific natural frequency, mode shape and damping ratio ^[5]. Modal analysis
78 is to decompose the complex vibration of a specific structure into individual vibrations. The modal
79 analysis can determine the vibration characteristics of the structural system, and provide a basis
80 for subsequent kinematics and dynamics analysis.

81 The modality is an intrinsic property of the object itself, it is only related to the shape, material
82 properties, and constraint characteristics of the structure. It is independent of other conditions, so
83 simplify the complex dynamic equation to the undamped case as given by equation (2).

$$84 \quad [M]\{\ddot{u}\} + [K]\{u\} = 0 \quad (2)$$

86 In the equation $[M]$ —Structure mass matrix;

87 $[K]$ —Structural stiffness matrix;

88 $\{\ddot{u}\}$ —Nodal acceleration vector;

89 $\{u\}$ —Nodal displacement vector.

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

$$92 \quad [K] - \omega_i^2 [M] \{\varphi_i\} = 0 \quad (3)$$

93 From equation (3), the vibration frequency and mode of the vibration structure of each order

φ_i

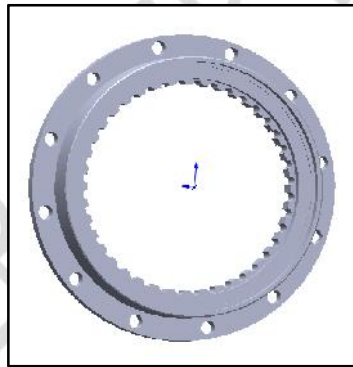
94 can be obtained [7].

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

99 3. Modal analysis of the needle wheel

100 3.1 Establishment of a three-dimensional model

101 Use SOLIDWORK 2016 [8] to create a 3D model of the needle wheel. To make it easier to follow
102 up and change the 3D model, use the "Equation" function in the "Tools" function to define the
103 basic parameters, array features, and stretch features of each sketch. When the model changes are
104 needed, the corresponding parameters can be changed directly in the equation, the control global
105 variables can be selected to achieve the rapid change of the model and achieve more efficient
106 work efficiency. The automatically generated needle wheel simulation model is shown in Fig.2.
107 The model stored as the "x_t" format in order to import into the Workbench working space easily
108 [9].



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110 Fig. 2 Simulation model of the needle wheel

111 3.2 Add material properties

112 This paper uses RV110E reducer as a model. The material defining the needle wheel is QT450-10
113 [10]. QT450-10 is ductile iron with good plasticity and toughness, good weldability and
114 machinability. It is often used in the manufacture of wheels for automobiles, clutch housing and
115 reducer housing. Its material properties are shown in Table 1.

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Table 1 QT450-10 material properties

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

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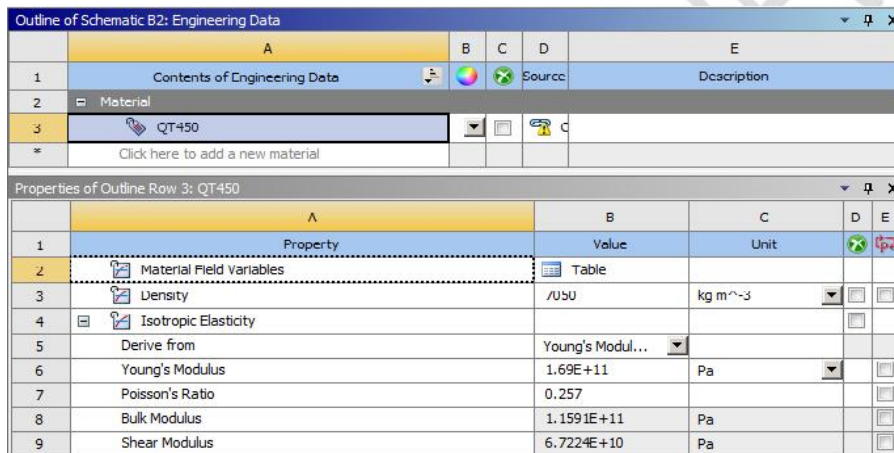


Fig. 3 Define the material properties of QT450-10

135 3.3 Meshing

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

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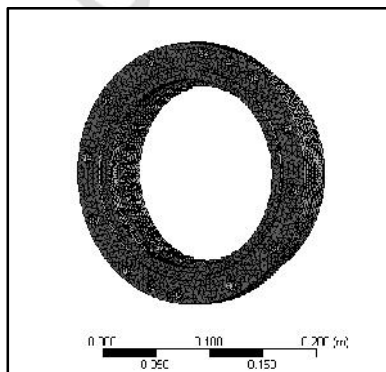


Fig. 4 Overall meshing

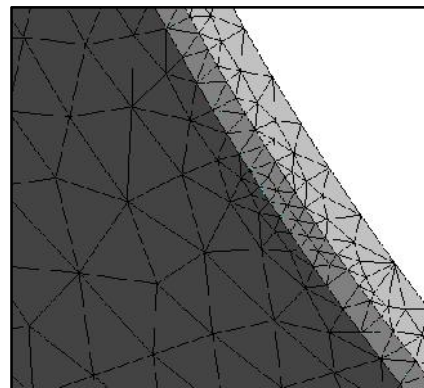
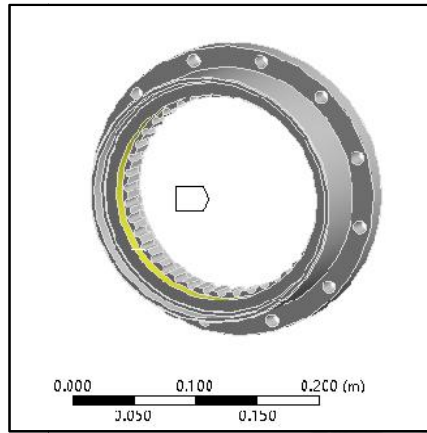


Fig. 5 Meshing at the chamfer

146 **3.4 Constraint form**

147 The difference between the constraint forms will lead to different modal analysis results ^[11]. The
148 constraint form of the needle wheel is divided into two types and only the constraint form of the
149 needle wheel output is considered in this paper. That is, the needle wheel is used as the output, not
150 only must it be fixed by the needle sheath, but also subject to bearing constraints, as shown in
151 Fig.6.



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Fig. 6 Constraint form when the needle wheel is output

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155 **3.5 Modal analysis**

156 After the modal analysis of ANSYS Workbench, the first 10 natural frequencies and modes of the
157 needle wheel are obtained. As shown in Table 2, each mechanical structure has different natural
158 frequencies under certain constraints, but generally, only the minimum natural frequency is
159 concerned. Because at this natural frequency, the structure is most prone to resonance, and the
160 mode of the minimum vibration frequency is shown in Fig.7.

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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

162	5	1669.3	Bending around the Z axis
163	6	1917.1	Telescopic along the XOY plane
164	7	1917.5	Telescopic along the XOY plane
165	8	4077.2	Distorted along the XOY face
166	9	4085.1	Distorted along the XOY face
167	10	4332.1	Distorted along the XOY face

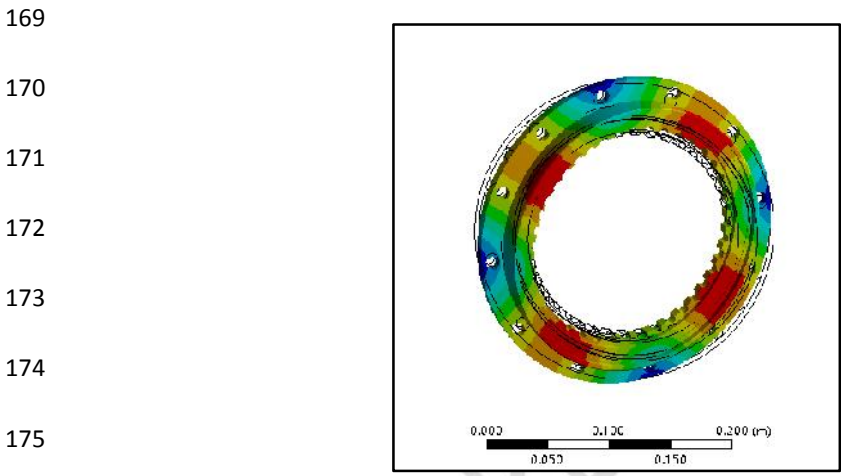


Fig. 7 Mode shape of the needle wheel output

177 **4. Modal result analysis**

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

182 In the 2K-V type reducer, there are gears of the first-stage transmission and the second-stage
 183 transmission. There are meshing frequencies. The calculation formula of the first-stage meshing
 184 frequency f_{m1} and the second-stage meshing frequency is defined as the equation (4) and (5).

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

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

187 In the equation, f_{out} —output speed (rad/s),

188 It can be calculated that the first stage meshing frequency and the second stage meshing frequency

189 are 1466.66 Hz and 1430 Hz respectively.

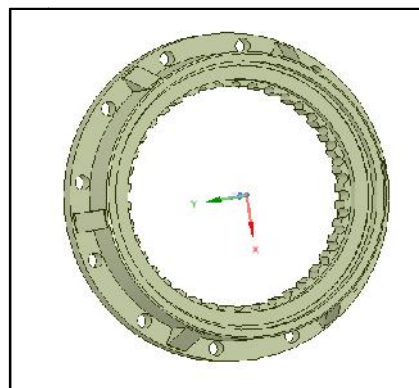
190 Comparing the minimum natural frequency of the needle wheel with 1384.4Hz and the natural
191 meshing frequency of the first stage transmission of 1466.66Hz, it can be seen that the natural
192 frequency of the needle wheel is within the range of gear meshing frequency, so it is easy to
193 generate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

195 5. The needle wheel optimization

196 In order to avoid the lack of transmission accuracy, which is caused by the natural frequency of
197 the needle wheel and the resonance phenomenon of the whole machine, the optimization design of
198 the needle wheel should be considered. According to the basic principle of modal analysis, the
199 modality is the inherent property of the structure, only with the material of the machine
200 component, the constraint mode and the shape are related. For the 2K-V type reducer, the
201 transmission form is determined, so the constraint mode for the needle wheel is also fixed, so it is
202 necessary to make appropriate improvements to its structural form^[12].

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

206 Since the 2K-V type reducer has a very tight structure so there is no space for the inner cavity of
207 the needle wheel to change the structure. Therefore, it is possible to add 6 reinforcing ribs on the
208 outer side of the needle wheel and increase the edge radius of the pin-toothed boss appropriately.
209 The new needle wheel model is shown in Fig.8. Adding the rib and increasing its thickness can
210 improve its stability. The calculation results are shown in Table 3. From the results, the natural
211 frequency of the needle wheel is increased from 1384.4 Hz to 1664.4 Hz, increased by 20%, the
212 natural frequency comparison before and after optimization is shown in Fig.9. It is far from the
213 first-stage gear meshing frequency, which can better avoid the resonance phenomenon caused by
214 frequency coincidence.



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220 Fig. 8 3D model after modification

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

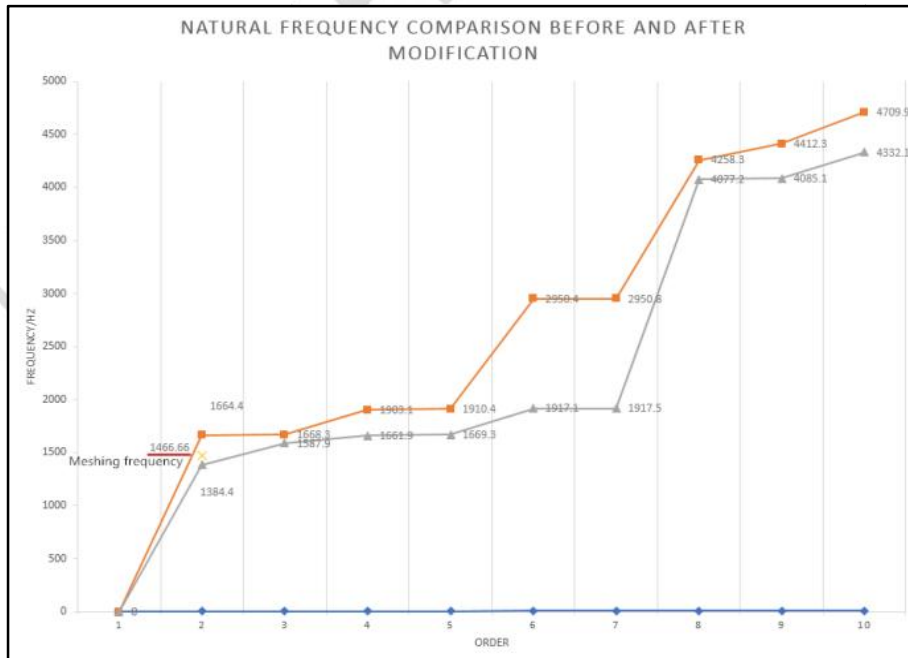


Fig. 9 Natural frequency comparison chart before and after optimization

225 The optimized vibration pattern is shown in Fig.10. It can be seen that after changing the shape and
226 optimizing the needle wheel, not only the natural frequency is increased, but also the place, where
227 the deformation is concentrated, is transferred from the skeleton oil seal link to the part of the
228 outer shell of the needle wheel and the ribs. Improving the stability of the needle wheel and
229 increasing the service life of the whole machine.

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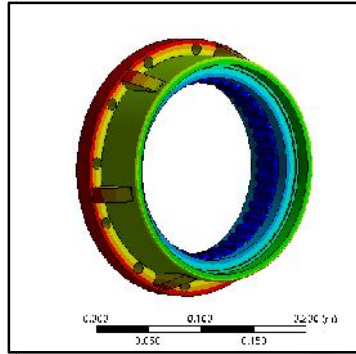
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Fig. 10 Vibration mode of the needle wheel after modification

237 6. Conclusion

238 In conclusion it can be said that the RV110E reducer can be used as a model, the natural
239 frequency of the needle wheel has been analyzed, and compared with the gear meshing frequency
240 of the whole machine. It is easy to cause the resonance between the needle wheel and the whole
241 machine under the output condition of the needle wheel. Through the various modes of the needle
242 wheel, it has been found that the part of the outer shell is weak, which is between the needle wheel
243 and the skeleton oil seal, and it is easy to be deformed. The optimization of this part should be
244 considered. As can be seen from the vibration mode of the needle wheel optimized by changing
245 the structural form, the deformation concentration position is changed and transferred to the part
246 where the outer shell of the needle wheel is connected with the stiffener. This method can improve
247 the stability of the needle housing and increase the service life of the machine. It is found when
248 the needle wheel is used as an output, the vibration frequency is within the gear meshing
249 frequency range, which is easy to cause resonance, thereby affects the transmission precision of
250 the whole machine. The part of the outer shell of the needle wheel and the oil seal of the skeleton
251 is the weakest and prone to deformation. By adding 6 reinforcing ribs between the needle wheel
252 flange and the outer casing, increasing the flange outer diameter at the same time, the natural
253 frequency can be increased; the deformation concentrated region can be transferred to the outer
254 casing and the reinforcing rib. The connected parts avoid resonance and increase the service life of
255 the needle wheel.

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