Synthesis of elements for waver gears of tunneling assemblies

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Abstract. Wave gears have high load capacity and small weight and dimensions parameters, therefore they are increasingly used in mining aggregates. The method of synthesis of elements of the wave transfer, which is based on the method of vector contours, is given in the work. The method takes into account the design features of the finger supports and the achievement of continuity of contact of the fingers with the generator, the rigid wheel and the holes of the guide disk. The proposed technique allows creating wave transmissions with a range of transmission ratios of 6–80. The adequacy of the synthesis technique is proved by the operability of waveguide samples, whose flexible wheels are made in the form of a finger chain. A new wave transmission is used in the developed microtunneling equipment.

1. Introduction

Wave gears, although recently invented, enjoy increasingly wider application. They ensure transmission ratios from 80 to 300, possess high loading capability, have efficiency to 0.9 and make it possible to reduced weight and size of drives by 1.5–2.5 times as compared with the regular toothed gearings [1–5]. Due to these advantages, wave gears can be used in power reducers in mining machines. For example, wave gear is included in cutter drive gear box of heading machine SM-130 [6]. A wave gear with spacer links is used in transmission of the tunneling machine—geokhod [7].

Design of a wave gear is the same since invention. A wave gear is composed of three main elements: flexible wheel rigidly connected with the output shaft; rigid wheel fixed in the body and a wave generator in the form of a cum with the input shaft. The application area of the wave gears is limited by transmission ratios higher than 80 [3–5]. The underlying condition is the design of the flexible wheel which as a thin-wall envelope with toothed periphery. At the transmission ratios lower than 80, flexible wheels can break down due to high bending stresses.

In order to ensure transmission ratios of wave gears from 6 to 80, it is proposed to use a finger chain in the capacity of the flexible wheel [8]. In this case, deformation of the flexible wheel takes place owing relative turn of the fingers. Working ability of a wave gear is governed by quality shaping of teeth on the flexible and rigid wheels [4, 5, 8].

2. Design features of toothed gears

Having the most accurate description of teeth geometry on flexible and rigid wheels is very important for syntheses of force wave teethed gears. The conventional synthesis of wave gears assumes that the flexible wheel deformations are insignificant, and engagement of flexible and toothed is considered as plane for this reason. In the developed chain wave gear, fingers represent the teeth of the flexible wheel; fixed on the backer plate, fingers move not in parallel to the gear axis but carry out rotational motions along conical trajectories. The inclination of the fingers to the gear axis varies continuously and is 2–5°. The faces in the new gear are synthesized based on the spatial motion of the fingers,
which ensures that the fingers have linear contact with the faces of the rigid wheel teeth, holes of the guide disk and generator.

In the wave gear structure in Figure 1, the flexible element is a chain of fingers coupled by plates. The fingers are mounted on the guide backer plate. Each plate couples two fingers and forms a chain hinge. The rigid wheel has internal teeth and is fixed in the body. As against the conventional flexible wheel, the finger chain lacks torsional stiffness; for this reason, the new gear is equipped with the guide disk with special-shape holes arranged on the output shaft. The guide disk is manufactured as a complete unit with the backer plate at which, using third-class spherical kinematic couples, the ends of the fingers are clamped. On the other side, the fingers interact with the cam generator on the input shaft. The number of the fingers exceeds the number of the rigid wheel teeth and equals the number of the guide disk holes.

**Figure 1.** Wave gear: 1—finger; 2—plate; 3—backer plate; 4—generator; 5—guide disk; 6—input shaft; 7—output shaft; 8—rigid wheel.

The transmission ratio is given by the expression [3–5 with number \( z_g \) of the flexible wheel teeth is replaced by the number \( n_g \) of fingers in the chain; “minus” points at rotation of the input and output shafts in different directions:

\[
i = \frac{n_g}{K_z U},
\]

where \( K_z \) is the divisible factor equal to difference between the numbers of rigid wheel teeth and fingers in the same deformation wave; \( U \) —is the number of deformation waves.

**Figure 2.** Sketch of determining trajectories of finger axes: (a) calculation coordinate systems; (b) motion of finger axes in coordinate system connected with guide disk.
3. Finger motion modeling

The study of the law of finger motion is based on the coordinate method applied in the theory of toothing [9]. Let there be introduced three coordinates $XYZ$, $X_1Y_1Z_1$ and $X_2Y_2Z_2$ connected, respectively, with generator, rigid wheel and guide disk (Figure 2a).

The axes $Z, Z_1$ and $Z_2$ coincide with the axis of the chain wave gear. The planes $XY, X_1Y_1$ and $X_2Y_2$ coincide among themselves and with the plane in which the finger-and-backer plate clamp points $C$ being the centers of spherical kinematic pairs. The spacing of the neighbor points $C$ is equal to the chain pitch $p_C$.

Let us consider motion of fingers in the coordinates $X_2Y_2Z_2$ as rotational motions of solids relative to immobile points $C$ (Figure 2b). The axes of the fingers move along the conical trajectories with the tips at the points $C$ along the closed ovals described by the centers $W$ of the chain hinges [8].

Let the point $W$ move in the coordinates $X_2Y_2Z_2$ along the trajectory:

$$
\begin{align*}
W_x &= f_{x_1}(t), \\
W_y &= f_{y_2}(t), \\
W_z &= f_{z_2}(t).
\end{align*}
$$

(2)

The coordinates of the point $C$ in the system $X_2Y_2Z_2$ can be represented by the coordinates of radius–vector $OC$:

$$
\begin{align*}
x_{2C} &= R_x \sin \phi_C, \\
y_{2C} &= R_y \cos \phi_C, \\
z_{2C} &= 0.
\end{align*}
$$

(3)

The coordinates of the point $M$ in the axis of the finger can be defined by the vector:

$$\overline{OM} = \overline{OC} + \overline{CM}.$$  \hspace{1cm} (4)

Here, the vector $\overline{CM}$ coincides with the vector $\overline{CW}$.

Denote the vector length $|\overline{CM}| = L_m$ and present the conical surface as the geometrical places of the points $M$. According to (4):

$$\begin{align*}
x_{2M} &= x_{2C} + \frac{x_{2W} - x_{2C}}{L} L_m, \\
y_{2M} &= y_{2C} + \frac{y_{2W} - y_{2C}}{L} L_m, \\
z_{2M} &= \frac{L_m}{L} \sqrt{L^2 - (x_{2W} - x_{2C})^2 - (y_{2W} - y_{2C})^2}.
\end{align*}$$

(5)

The motion trajectory of the finger axes in the coordinates $XYZ$ can be found by transform of coordinates for the point $M$.

It is more direct and convenient for the further determination of the generator face to use the method of finding the finger axis trajectory as the displacement of generatrix coincident with the finger axis along two directrixes which are the paths of the points $W$ and $C$ in the coordinates $XYZ$ (Fig. 3a).

The equation of the surface, which is the finger axis trajectory, can be written as the coordinates of the point $M$ radius–vector in the system $XYZ$

$$\overline{OM}' = \overline{OC} + \overline{CM}'.$$

(6)

The equation of the generator face is found similarly to the finger axis trajectory in the system $X_2Y_2Z_2$. 

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Figure 3. Sketch of finding trajectory of finger axes: (a) in coordinate system connected with generator; (b) in coordinate system connected with rigid wheel.

The coordinates of the radius–vector $\overrightarrow{OM''} = \overrightarrow{OC''} + \overrightarrow{CM''}$ in the system $X_1Y_1Z_1$ (Fig. 2b) will be:

$$
\begin{align*}
x_{1M} &= x_{1C} + \frac{x_{1W} - x_{1C}}{L} L_m, \\
y_{1M} &= y_{1C} + \frac{y_{1W} - y_{1C}}{L} L_m, \\
z_{1M} &= \frac{L_m}{L} \sqrt{L^2 - \left(\frac{x_{1W} - x_{1C}}{L_m}\right)^2 - \left(\frac{y_{1W} - y_{1C}}{L_m}\right)^2}.
\end{align*}
$$

(7)

Motion of fingers in the coordinate systems $XYZ$ and $X_1Y_1Z_1$ can be characterized as compound motion of solids. In this case, relative motion of fingers in the system $X_2Y_2Z_2$ is their rotation relative to the points $C$. Translation motion is the rotation of the points $C$ around the gear axis. This is the case of summation of rotations around unparallel axes.

The synthesis of work faces should ensure conditions when lateral cylindrical surfaces of the flexible chain fingers is in continuous contact with generator, rigid wheel teeth and guide disk holes. The work faces of the generator, rigid wheel teeth and guide disk holes will be the enveloping surfaces of the interfaced fingers of the chain [8]. Since the faces of the fingers are cylindrical, the problem reduces to determining equally distant surfaces to the trajectories of the finger axes. This method can be assumed as the analytical synthesis of engagements based on the classical apparatus of differential geometry. This method also enables synthesizing work faces of the generator cam.

The synthesis method is implemented in engineering of prototype wave gears with the transmission ratios 6, 8 and 10 (Fig. 4). The working ability of these wave gears proved efficiency of the procedure. The wave gear with the flexible wheel represented by the finger chain was used in the microtunneling equipment [10].

Figure 4. Prototype wave gear with transmission ratio 8.
4. Conclusions

Representation of the motion of fingers in the guide disk relative to immobile points takes into account structural features of spherical supports of the fingers on the backer plate and the one-way connection between the fingers and the plates.

Motion of the fingers in the coordinate systems connected with generator and rigid wheels is compound, including relative motions of the fingers relative to the rigid wheel and translational rotation of spherical support of the fingers around the wave gear axis.

The developed procedure ensures continuity of contact between fingers, generator, rigid wheel and guide disk holes in the wave gear.

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