Design of Driving and Circulation System for Polar Ice Drilling with a Rolling Movable Teeth Transmission

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Abstract: Cable-suspended electromechanical coring drills are widely used in polar ice coring drilling. Previously, when the drive and circulation system of the cable electromechanical coring drills used to be driven by a reduction transmission device, during the process of meshing, each pair of gear teeth was prone to fatigue damage due to the interaction vibration between the teeth. In addition, the high torque would cause the destruction of the deceleration transmission, and owing to the relatively short life, the reliability of the devicewould be poor. Because of the staff work in the polar region having an extreme cold and anoxic environment, the labor intensity of the personnel and number of maintenances of equipment should be minimized in polar drilling. Hence, it is paramount to improve the reliability of the reduction transmission device. In this study, the driving and circulation system for polar ice drilling was designed. A new type of transmission structure is proposed, namely, the rolling movable teeth reduction transmission device. There are prospects for application in the polar region.

1. Introduction

Cable-suspended electromechanical coring drills were successfully developed in the U.S. Cold Regions Research and Engineering Laboratory, RREL over 50 years ago. Various cable electromechanical drills with drilling fluid downhole circulation have been developed in the United States, Denmark, Russia, Japan, and other countries. Table 1 lists the application status of the driving and circulation systems of the cable electromechanical drills used in various countries (Kudryashov et al.,2002;Herbert et al.,2002;Yoshiyuki et al.,2002;Talalay,2013).

TABLE I. Application status of the driving and circulation systems of the cable electromechanical drills used worldwide.

Country	**U.S.**	**Japan**
Type of reduction transmission device	Harmonic transmission	Harmonic transmission
Type of drilling fluid downhole circulation	Local positive circulation	Local counter circulation
System pump	Pump system	Non-pump system
Russia	**Denmark**	**China**
Planetary gearing	Harmonic transmission	Harmonic transmission
Local counter circulation	Local counter circulation	Local counter circulation
Pump system	Pump system	Pump system

Currently, the type of transmission in the reduction transmission device of the cable electromechanical drills is generally harmonic transmission or planetary gearing. During the meshing process, each pair of gear teeth of a planetary gear affected by their interaction vibration is prone to fatigue damage. In addition, the high torque will cause the destruction of the deceleration transmission, and thereby, relatively shorten its operation life. The flexible wheel of a harmonic reducer is prone to fatigue failure, load of the supporting bearing is extremely high, and wear-resisting life of the solid lubricating film on the gear surface of a reducer is short. Therefore, the reliability of the previous reduction transmission devices of cable electromechanical drills is low. This paper proposes a novel type of transmission structure, namely, the rolling movable teeth reduction transmission device.

Movable teeth transmission is a type of gear transmission that has evolved from K-H-V small-teeth difference planetary gear drives. A movable teeth transmission has some advantages such as compact construction, light weight, small volume, wide transmission ratio, high transmission efficiency, multi-teeth meshing, strong bearing capacity, long life, and high torque. Because of the above characteristics, movable teeth transmission has attracted the attention of the global engineering community. In the 1980s and 1990s, several types of live tooth transmission were proposed. The typical movable teeth transmission forms are pushrod, rolling, swing, and cylindrical sliding movable teeth transmissions and the planar ball drive (Keith, 1982; Imase, 1997; Terada et al., 1988). This study selects rolling movable teeth transmission used as multi-teeth meshing transmission, which can reduce the torque of deceleration drive to multiple teeth, and the torque of each tooth being greatly reduced making the life of reduction transmission device greatly increased. Because more than half of the movable teeth are in the meshing state, the reduction transmission device has strong impact capability and strong bearing capacity. The movable tooth is placed in the internal teeth ring, which makes the reduction transmission device a compact construction of light weight and small volume. The reduction transmission device has wide transmission ratio and high transmission efficiency. Therefore, the rolling movable teeth transmission is applied in the ice drilling of the polar drilling equipment and the application, which satisfies the preconditions of light, high efficiency, energy conserving and environment protecting, and which entails extensive prospects.

2. Structure of the Driving and Circulation System of a Polar Ice Drilling

Fig.1 shows the structure of a drill driving and circulation system. Its main components are an electric motor, a reduction transmission device, a down-hole pump, a chip chamber, a core barrel, and a drill bit. The complete removal of ice chips is a key step in the drilling process. Otherwise, ice chips will accumulate in the upper part of the drill bit, which may cause accidents owing to the sticking of the drill tools (Talalay et al., 2015). An electromechanical drill generally adopts an independent motor drive pump, and the pump is on the top of the motor. The ice chips need to pass through the reducer and motor before entering the chip chamber. The running distance of the ice chips is long, and the resistance is formidable in the central channel of the motor and reducer, which causes the suction effect of the pump to be extremely weak and an ineffective cleaning of the bottom of the hole. In this work, to improve the performance of the driving and circulation system of the electromechanical drill, the structure of the driving and circulation system of the φ127 cable-suspended electromechanical coring drill is adopted. A motor is used to drive the pump and rotary cutting of the bit. The pump is placed on the top of the chip chamber to shorten the transport distance of the ice chips. The diameter of the driving and circulation system of the drill is 127 mm, and the motor drives the core barrel and drill bit to result in a high-speed rotary cutting while driving the pump to rotate at a high rotation speed. When the pump suction works, the drilling fluid carrying the ice chips from the center channel of the ice core tube extends the drill rod. This aggravates the device and pushes the chips first into the chip chamber. Through the filter hole, designed on the outdoor wall of the chip chamber, into the chip chamber outdoor space. Finally, the pump is discharged into the circular space of the drill and borehole, forming a local reverse circulation, whereas the ice chips remain at the end of the chip chamber to be returned to the surface for treatment.

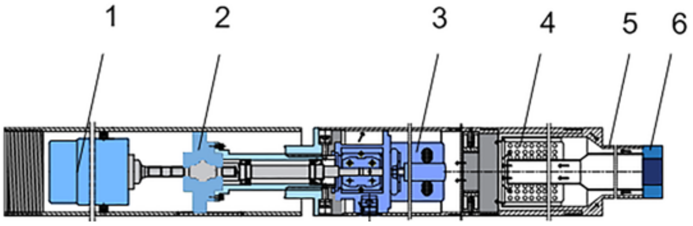

Fig. 1. Schematic of the drill driving and circulation system: (1) electric motor;(2) reduction transmission device;(3) down-hole pump; (4) chip chamber; (5) core tube;(6) drilling bit.

3. Design Reduction Transmission Device of an Ice Drill

3.1 Principle of Rolling Movable Teeth Transmission

When the motor starts, the input shaft of the reduction transmission device begins to rotate at a constant speed. The input shaft drives the geometric center of the eccentric wheel to rotate at the constant angular velocity of the fixed center. A radial thrust is generated by the change in the radius of the eccentric wheel, which forces the rollers moving in the meshing state with the center wheel to move along the guide groove of the cage in the radial direction, whereas the axial roller moves along the center gear rolls smoothly. Simultaneously, the radial thrust is pushed through the guide slot of the tooth rack to drive the rollers to reverse rotate at the same angular speed, so that the reduction transmission device completes the rotational speed transformation. Driven by the guide groove of the cage, all the rollers in the non-meshing state of the center wheel return to the starting position in sequence (Jifang Qu, 1993).

3.2 Basic Parameters and Geometric Dimensions

The φ127 cable-suspended electromechanical coring drill using the AC380V powered MS4000 Grundfos submersible motor with a power of 3 kW, diameter 101.6 mm, and speed 2850 r/min is employed. The drill slows down to 90 r/min in case snow cover and ice drilling. The maximum diameter of the reduction transmission device is within 110 mm. The basic parameters and geometric dimensions of the reduction transmission device are listed in Table 2.

TABLE II. Basic parameters and geometric dimensions of the reduction transmission device

Parameters and Dimensions	**Numerical number**
Drive Ratio i	32
Number of Rollers Z_G	32
Number of Teeth in the Center Wheel Z_K	31
Pitch Circle Diameter of the Center Wheel D_k/ mm	90
Chord Pitch of the Center Wheel t_g/mm	9.1
Diameter of the Rollers d_g/mm	4
Eccentric Distance e/mm	0.95
External Diameter of the Eccentric Disc D_j/mm	84.1
Root Diameter of the Center Wheel D'_k/mm	94
Tip Diameter of the Center Wheel D''_k/mm	90.2
Height of a Roller b/mm	4
External Diameter of the Cage D'_g/mm	88.5
Internal Diameter of the Cage D''_g/mm	86.5

3.3 Design Tooth Profile

The tooth profile of the center wheel is designed on the basis of the known parameters. In the process of tooth profile design and graph drawing, the basic parameters and geometric dimensions can be modified, and the tooth profile design and parameter determination are interconnected to meet the requirements of the drill. The rectangular coordinate system OXY are selected, as shown in Fig. 2.

The eccentric wheel is rotated clockwise around eccentricity point O, and the rollers are rotated counterclockwise in the cage. In the rolling process of the rollers, the rollers are always tangent to the eccentric wheel. The distance between geometric centers O1 and O2 of the eccentric wheel and roller, respectively, remains unchanged. The distance between geometric center O2 of the roller and eccentricity point O changes, and the center wheel, which is always in contact with the roller, is fixed. Therefore, the shape of the center wheel profile is the outer envelope curve formed by the moving track of the rollers along O1'. Therefore, for the center of the tooth profile curve equation, the curve equation is computed firstly out roller trajectory. The number of teeth in the center wheel is ZK, number of rollers is ZG, eccentric wheel turns by angle φ, and the cage turns by angle α.

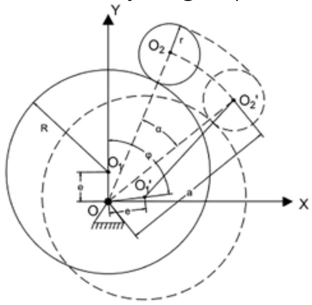

Fig. 2. Motion diagram of the equivalent mechanism of movable tooth transmission

Known formula

$$i=\varphi/\alpha=Z_G/(Z_G-Z_K)=Z_G \tag{1}$$

The geometric relationship in Fig.2 can be obtained as,

$$(R+r)^2=e^2+a^2-2\cdot e\cdot a\cdot\cos(\varphi-\alpha) \tag{2}$$

Where after inserting $\varphi-\alpha=(Z_G-1)\alpha$, we obtain

$$a=e\cos((z_G-1)\alpha)+\sqrt{(R+r)^2-e^2\sin^2((z_G-1)\alpha)} \tag{3}$$

The actual tooth profile of the center wheel is the outer envelope curve of the rollers. The enveloping curve of the movable tooth rollers along the track is a circle with radius b as the center of the theoretical tooth profile. The center coordinates are determined by the trajectory equation. From differential geometry, the equation of the envelope curve with α as the parameter can be expressed as

$$\begin{cases} f(X,Y,\alpha)=(X-x)^2+(Y-y)^2-b^2=0 \\ \partial f(X,Y,\alpha)/\partial\alpha=-2(X-x)\,dx/d\alpha-2(Y-y)\,dy/d\alpha=0 \end{cases} \tag{4}$$

Where X and Y are the cartesian coordinate values of the point on the envelope curve. Where

$$\begin{cases} x=a\cos\alpha \\ y=a\sin\alpha \end{cases}: \quad \begin{cases} X=a\cos\alpha+b\cdot(a\cos\alpha+(\partial a/\partial\alpha)\sin\alpha)\Big/\sqrt{(\partial a/\partial\alpha)^2+a^2} \\ Y=a\sin\alpha-b\cdot((\partial a/\partial\alpha)\cos\alpha-a\sin\alpha)\Big/\sqrt{(\partial a/\partial\alpha)^2+a^2} \end{cases} \tag{5}$$

Where $\frac{\partial a}{\partial\alpha}=-(Z_H-1)e\sin((Z_H-1)\alpha)-\frac{e^2(Z_H-1)\sin((Z_H-1)\alpha)\cos((Z_H-1)\alpha)}{\sqrt{(R+r)^2-e^2\sin^2((Z_H-1)\alpha)}}$ The basic parameters and geometric dimensions of the upper section are replaced by formula (5). The Mathematica program is compiled, and the center wheel tooth profile curve is drawn as shown in Fig. 3.

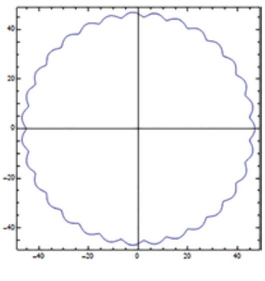

Fig. 3. Center wheel tooth profile curve.

According to the center wheel profile equation, when the ratio of the movable teeth transmission is given, the shape of the center wheel is affected by the radius of the eccentric wheel, eccentric distance of the eccentric wheel, and radius of the rollers. In the design of the center wheel, the tooth profile should be selected to avoid the interference in the tooth profile curve. The curvature of the center wheel curve represents the bending degree of the tooth profile near the point. It describes the geometric characteristics of the tooth profile curve, and it is an important parameter for studying the bearing capacity and lubrication state of the movable tooth transmission. From differential geometry, curvature K of the center tooth profile curve is given a

$$K = \frac{\left(dx/d\alpha \cdot d^2y/d\alpha^2 - d^2x/d\alpha^2 \cdot dy/d\alpha\right)}{\left(\left(dx/d\alpha\right)^2 + \left(dy/d\alpha\right)^2\right)^{3/2}} \quad (6)$$

The basic parameters and geometric dimensions of theupper section are substituted into formula (6). The Mathematica program is compiled. The center wheel tooth profile curvature, K, changes with the variation in the angle of the cage, as depicted in Fig.4. As can be seen from the figure, the maximum value of the curvature of the tooth profile appears at the root of the tooth, which is 0.482785 mm-1, and the corresponding radius of curvature is 2.07 mm. At the top of the tooth, the curvature of the tooth profile reaches the minimum value of -0.457664 mm-1, and the corresponding radius of curvature is 2.19 mm. During the transition of the tooth profile from the root to the top of the tooth, the curvature decreases monotonously and reaches the zero point at the inflection point. To ensure that the working profile of the center wheel does not interfere with the tooth profile at the top of the tooth, the value of the radius of the roller should be satisfied with the condition, r < 2.19 mm.

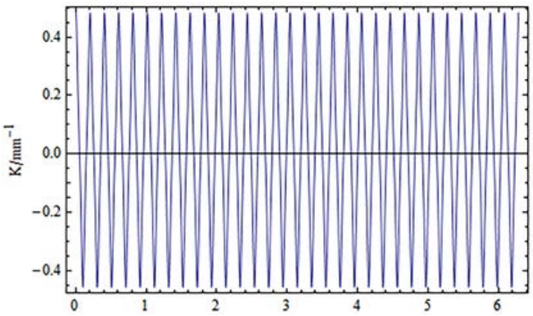

Fig. 4. Center wheel tooth profile curvature K–α

4. Design of the Polar Ice Drilling Drive and Circulation System

For the main motor of the polar ice drilling driving and circulation system, the MS4000 Grundfos submersible motor powered by AC380V is chosen, and the motor adopts the closed pre-lubrication mechanism to apply the pressure of 15 MPa. For the drilling, two different types of centrifugal pumps are installed according to the actual drilling conditions. One is SPK 2-23/23 with a standard flow of 33 L/min and outlet pressure of 0.65 MPa. The other type of pump is SPK 4-11/11 with a standard flow of 66.7 L/min and outlet pressure of 0.33 MPa. Two pumps are Grundfos SPK pumps with an outside diameter of 100 mm. These are mainly used for pumping the coolant and lubricating fluid and performing similar applications. The pump head is made of AISI 316 LN. It is suitable for pumping corrosive liquids and liquids containing a high solid content.

According to the polar ice drilling work design characteristics of driving and circulation system, the main shaft of the motor is connected with the input shaft of the reduction transmission device via a spline sleeve. The input shaft passes the motor speed to the feed pump via the solid axis to achieve power transmission. The movable tooth transmission reduces the motor spindle speed to the bit speed, and is output by the cage. The cage is connected with a hollow shaft. The hollow shaft is connected with the outer tube of the drill to provide the speed for the bit. The ice drill reduction transmission device effectively implements a motor that provides power for both the pump and drill bit. The assembly diagram of the ice drilling driving and circulation system is shown in Fig. 5.

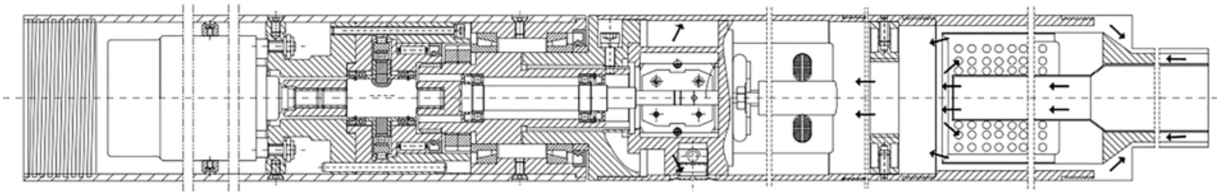

Fig. 5. Assembly diagram of the ice drilling driving and circulation system

5. Conclusion

To optimize the design of an ice drilling driving and circulation system, first, this paper introduces and compares the structure and performance of the driving and circulation system of cable electromechanical drills available in the global market. Subsequently, the paper proposes a new reduction transmission device, i.e., the movable tooth transmission reduction device. Next, the reduction transmission device is designed, and the study provides a theoretical basis and presents a solid model for further research on improving device reliability.

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