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Load Allocation and Equilibrium for Planetary Gear Reducers of Earth-Pressure-Balance Shield Machine

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Abstract

To optimize the 3-stages planetary gear reducer (PGR) in the Earth-Pressure-Balance Shield Machine (EPBSM), it is necessary to firstly define the EPBSM environment. The needed torque of the cutter-head, therefore, is analyzed when the EPBSM cutting the earth body. The load of any PGR is allocated according to the equivalent principle in the size between the force and its response one and the distributing uniformity of the PGRs around the main axle gear. Because the structure of the main drive system is equal to a huge planet-gear reducer made of 8 planetary gears, for the main axle connected with it gear, one side is connected with a bidentate coupling, the other is connected with an elastic shaft to realize the dual connection floatability of the main axle gear and support the whole main axle gear so that the relative displacement can be compensated to high degree among the PGRs resulting from the uneven force when the cutter-head cuts earth body.

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Keywords: earth-pressure-balance shield machine; planetary gear reducer; load; allocation; equilibrium.

1. Introduction

The Earth-Pressure-Balance Shield Machine (EPBSM) is a special tunneling engineering machine, which gathers many technologies in one, such as optics, mechanics, electric, fluid, sensor and information, and can

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excavate and cut soil, ship the residual soil, assemble tunnel lining, measure guidance rectification, and so on. It is involved in geology, civil construction, machinery, mechanics, hydraulic pressure, electrical science, control, measure, etc, and it is demanded that its design and manufacture are tailoring to the different geology so that it makes a very high request of reliability[1]. It is made up of shield body, cutter drive, double ventricle airbrake, the machine of piecing up the pipes, the organ of casting soil, post-match device, electrical system and other auxiliary equipment. Its operation principle is as follows. The output torque from the hydraulic motor is magnified by the planetary gear reducers (PGRs) to dive the cutter-head rotation when the propulsion hydro-cylinder of shied machine is opened to propel the shield machine forward. The soil is cut and falls into its chamber when the cutter-head continuously rotates. When the chamber is filled out, the screw conveyor is started to transport the soil to the belt one that can ship the soil to the boxes. They are transported to appointed place so that the soil is brought to earth surface by the shaft. The resistance will increase that the residual soil which is cut down from the excavation surface enters the chamber through the cutter groove when the soil in the chamber and screw conveyor accumulate to a certain degree, and while the pressure reach balance between the chamber, the excavation surface and the ground water, the excavation surface will keep stable so that the ground surface corresponding to the excavation one won't collapse or uplift. If the amount of the soil falling into the chamber from the excavation surface is equal to the amount of the soil shipped out of the chamber by the screw conveyor, the excavation work will be carried out smoothly[2]. The structure of EPBSM is shown as Fig.1[2,3], here, the main drive system is made up of 8 identical PGRs in the structure and the hydraulic motor.

Because the motive power of the EPBSM cutter-head originates from the output torque of the PGRs, while the needed torque of the cutter-head decides on the structures of the PGRs, therefore, besides grasping the basic principle of the EPBSM, we still analyze its force to guide the whole optimization for the high power and 3-stages PGRs in the EPBSM.

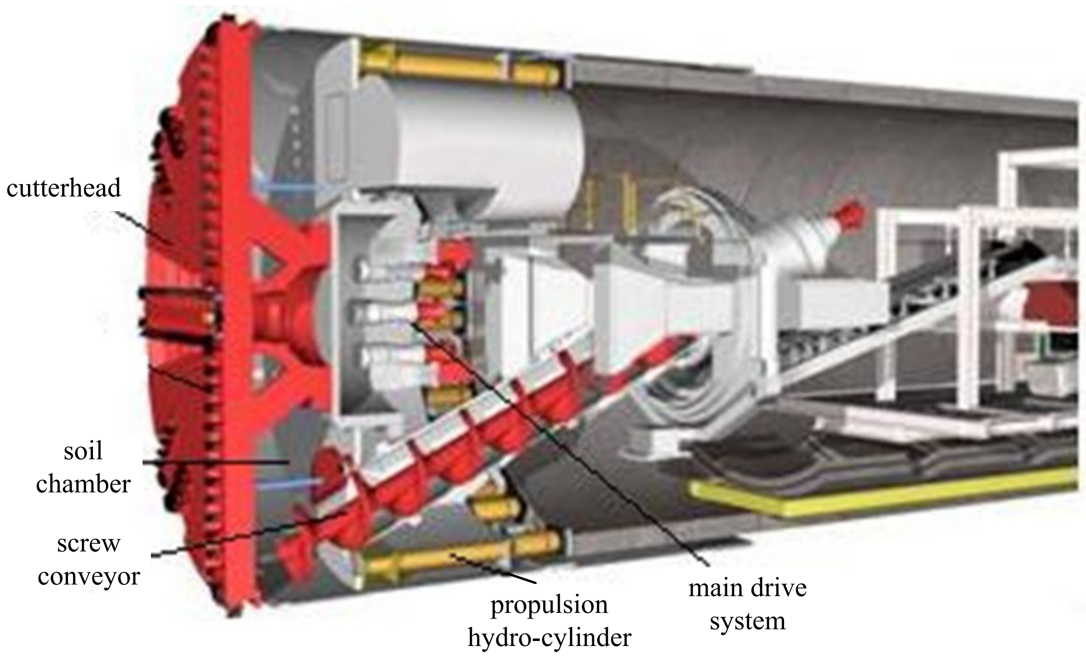

Fig.1 the structure of EPBSM

2. Force analysis of EPBSM

The force of the EPBSM mainly produces from the cutter-head, and the transmission route of the force is hydraulic motor→PGRs→ cutter-head. For the torque of the cutter-head, there exist in the 2 computational methods as follows [4].

① Computational method of design torque

$$T_N = T_1 + T_2 + T_3 + T_4 + T_5 + T_6 \tag{1}$$

$$T = K \cdot T_N \tag{2}$$

Here, T_1 is the torque produced by the soil shear force. T_2 is the shear torque generated by the cutting heads cutting the soil. T_3 is the frictional resistance torque produced by the cutter-head driving the sediment seal. T_4 and T_5 are the torque generated by the axial and radial load, respectively. T_6 is the torque done by the stirring bar agitating the soil. K is safety coefficient. T is the needed torque driving the cutter-head. The concrete computational formula of $T_1 \sim T_6$ are referred as the document [4].

② Computation method based on experience [4,5]

$$T = \alpha \times D^3 \times 10^4 \tag{3}$$

Where, T is the needed torque driving the cutter-head. D is the outer diameter of shield machine. α is the torque coefficient, whose value varies from the outer diameter of shield machine and soil body, for the EPBSM, its value region is 1.4～2.3.

3. Load allocation and equilibrium for PGRs of EPBSM

In the course of cutting soil body, the needed torque of the cutterhead in the EPBSM directly originates from the 8 identical 3-stages PGRs in the structure that uniformly rank around the main axle gear, namely, the 8 PGRs are the modified motive power equipment of the whole EPBSM, therefore, how to allocate and balance the load among them is the large artery that determines on healthy operation of the whole shield machine.

3.1. Load allocation for PGRs of EPBSM

Because the needed torque T of the cutterhead comes from the transmission torque of the gear axles of the output terminal of the PGRs, if the number of PGRs is n, the output torque of a single PGR is T_0, the graduated circle diameter of the gear in the shaft is d_1, the graduated circle diameter of the gear in the main axle is d_2, then for any a pair of engagement force which is normal to gear surface, the following relation exists between the force and its response one according to the equal principle in their numerical values.

$$\frac{T/n}{d_2/2}\frac{1}{\cos\alpha} = \frac{T_0}{d_1/2}\frac{1}{\cos\alpha} \tag{4}$$

$$\Rightarrow \quad T_0 = \frac{T}{n}\frac{d_1}{d_2} \tag{5}$$

When the load unbalance existing among the PGRs, Eq.(5) can be written as

$$T_0 = \beta \frac{T}{n} \frac{d_1}{d_2} \tag{6}$$

Here, T_0 is the output torque of a single PGR. T is the needed torque of the cutterhead. n is the number of PGRs. β is the uneven coefficient of load among PGRs. d_1 and d_2 are the graduated circle diameter of the gear in the output shaft and the gear in the main axle, respectively.

3.2. Load equilibrium for PGRs of EPBSM

As can be seen from Fig.1, the 8 three-stages PGRs are uniformly assembled around the main axle gear, which is driven by the gear of output shaft of PGR, its structure, therefore, is equivalent to a large planetary-type reducer that has 8 planet gears (the difference between them is that it hasn't planet carrier and inner gear, the 8 planetary gears can only rotate around its own axis and can't do around the main axle), its mechanism sketch is seen as Fig.2, so the factors that has an impact on the uneven coefficient K_p of the load among the planetary gears also influence the load nonuniformity among PGRs, for example the level of gear manufacturing precision, the degree of the load transmission, the stiffness of the component structure, gear material and tooth surface hardness, the run extent of the tooth surface, the level of engagement speed, the number of planetary gears, the property of the load-sharing device, and so on[6].

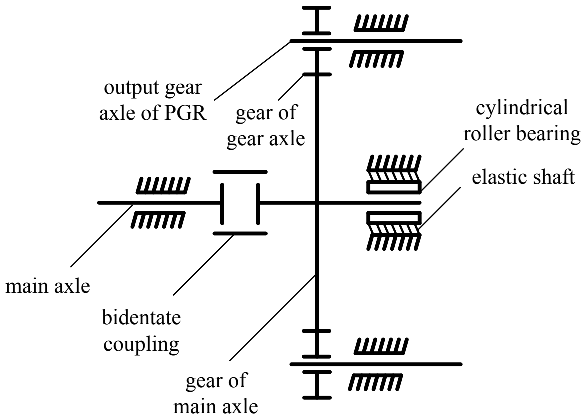

Fig.2 the diagram of connection mechanism and uniform load device between the output of PGR and the main axle of EPBSM

Because the shafting motion of the output gear axles of PGRs and the main axle of the shield machine cutter-head is low speed and heavy load, we can assemble a bidentate coupling[7] and an elastic shaft in the main axle, as is shown in Fig.2. On one hand, one side of the coupling is connected with the main axle driven by the gear of PGRs, the other side is done with the main axle driving the cutter-head so that the relative displacement resulting from the uneven force from the cutter-head can be compensated to high degree, on the other hand, an elastic shaft is installed in the other side of the main axle, which can not only keep floatability, but support the main axle gear. Therefore, the relative displacement among the gear axles of PGRs resulting from the uneven force can be compensated to realize the load-sharing, so the uneven coefficient β of the load can be processed according to the uneven coefficient $K_{p,}$ of the sun gear floatability in PGR, namely, β =1.1～1.15[8].

4. Illustrative example

For some EPBSM, the outer diameter of its cutter-head D =6.4m, the transmission ratio of the 3-stages PGR i =51.2,the tooth number of the output axle gear of the PGR z_1=37, the tooth number of the main axle gear z_2=331, gear modulus m=5mm,the number of PGRs n=8, It is demanded to estimate what is the torque value when the EPBSM operate in the common working condition, how to select the hydraulic motor to drive the PGR.

If let the torque coefficient α =1.85, the uneven coefficient β =1.125, then during the operation of EPBSM, the torque of its cutter-head is

$$T = 1.85\times 6.4^3\times 10^4 = 484.9664\times 10^4 \text{ N·m}$$

The output torque of a single PGR is

$$T_0 = \beta\frac{T}{n}\frac{d_1}{d_2} = 1.125\times\frac{484.9664\times 10^4}{8}\times\frac{5\times 37}{5\times 331} = 76233.8610 \text{ N·m}$$

So its input torque is

$$T_{01} = \frac{T_0}{i} = \frac{76233.8610}{51.2} \approx 1489 \text{ N·m}$$

Namely, to make the EPBSM operate normally, only the rated torque of the 8 hydraulic motors is no less than 1489 N·m can the 3-stages PGRs be driven.

Therefore, we can determine on the demanded transmission ratio of PGRs and optimize its structure according to the demand of the output torque of PGRs and the hydraulic motors.

5. Conclusions

The cutterhead of the shield machine, which is the object driven by the output torque of PGR, is analyzed from the torque, then the load is assigned for every PGR, the uneven ones among PGRs are balanced by means of the dual connection floatability mechanism and an elastic shaft to define the environment of EPBSM for optimizing PGR, therefore, the high-power 3-stages PGR can be optimized and its innovative work can be developed.

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