Development and Key Technology of the TBM 
Cutter Head Drive System

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Abstract: Tunnel Boring Machine (TBM) is an advanced modern tunnel construction equipment. As the most important core component of TBM, the cutter-head drive system and its performance directly affect the efficiency and quality of the dug rocks. This paper elaborates the principle, driving schemes and the developments of the cutter-head drive system of TBM. The problems encountered in the construction and the methods to solve these problems are presented in the paper. Finally, the key technologies and the trend to develop the cutter-head drive system are discussed.

Overview

The Tunnel Boring Machine (TBM) is large engineering equipment and advanced modern tunnel construction equipment integrated with multiple fields such as mechanism, hydraulic, electricity, inspection, control, etc. It mainly consists of main equipment and corollary equipment. The main equipment includes belt conveyor, shield, main beam, propulsion system, gripper shoes system, control room, etc. while the corollary equipment includes hydraulic power system, power supply system, control system, ventilation and dust collecting system, slag discharge system, water supply and drainage system, grouting support system, etc. which are all connected with each other with a group of steel structure trolleys and to the main equipment [1-3] as well. Compared with the traditional drilling and blasting method, construction with TBM method appears faster, safer and more reliable in good quality but at low cost and of least harm to the environment [4-5]. Therefore, the TBM and its relative technologies have become a trend under the background that the whole world pays more and more attention to the underground space exploration in a more environmentally friendly way, not pushing the earth too hard.

Since the beginning of the research on the TBM in the 60s of the last century, our country has grasped the core techniques, achieved localization and accumulated vast experience in the construction particularly due to the rapid development of infrastructure. However, contrary to that only a few corollary equipment are processed by ourselves, the large diameter TBM still has to be imported and the core techniques on design and manufacture of the large diameter TBM is still in the hands of a small number of foreign companies, especially the key component
of the TBM, the cutter head drive system which is related to its unneglectable functions of boring, heading stabilizing and ground slag stirring, keys to cutting capability, boring efficiency and construction cost. Moreover, because of the bad working environment which always leads to the cutter head malfunctioned or stuck, affecting the efficiency and construction progress of the TBM, the cutter head drive system has aroused the domestic scholars and constructors’ great attentions.

Initiating from its working principle, the article will analyze the problems that the cutter head drive system may have in the construction and the countermeasures that is needed, as well as introduce a whole view of its working and key technologies.

**TBM Cutter Head Drive System**

There are two major actions in the TBM’s work: one is to cut by the rotation of the cutter head and the other to move the head forward to form a tunnel. Both actions form the boring process, making the TBM move in a spiral line. The rotation of the cutter head is controlled by the cutter head drive system while the forward movement completed by the support-promoting-step change mechanism.

The Figure 1 shows the structure of the cutter head drive system which includes drive power (electric motor or hydraulic motor), reduction gear, gear pair (pinion and girth gear), main bearing, etc. The basic working process: through the reduction gear, the power coming from the electric or hydraulic motor results in deceleration and increased torque which will be transmitted to the girth gear through the pinions, enhancing the deceleration and torque increase so as to drive the cutter head with the help of several same drive units. The maximum peripheral speed of the out ring of the TBM cutter head is usually less than 2.5m/s, so its speed reducing ratio shall be coordinated with the rotation, otherwise the cutter head will be readily worn out. The total speed reducing ratio of the system shall be the speed reducing ratio of the reduction gear multiplied by the one of the gear pair system, and so it can be controlled by those two kinds of ratios [6].

![Figure 1. Structural representation of the TBM cutter head drive system.](image-url)
Problems That the Cutter Head Drive System May Meet in the Construction and the Countermeasures

During the boring by the TBM, the cutter head faces extremely harsh working conditions with its cutter head assuming the counterforce from the rocks on one hand and the outer ring of the cutter head bearing the contractility from the rock on the other. The high ground stress, high temperature and high quartz content require that the cutter head system be capable of withholding the heavy shock loads and transferring sufficient rock breaking energy. The bad working conditions such as the cutter head getting stuck really happens frequently under such environment, which dramatically impedes the construction progress. In this case, the TBM which is mostly applied in the geological conditions of high hardness, high temperature and high quartz content (‘three highs’) has to face extremely complicated conditions with uncertainties and break its cutter head frequently due to the heavy shocks coming from the hard rocks during the boring. Even the fragments of crushed rocks due to the frequent phenomenon of rock burst get the cutter head stuck, lowering down the efficiency of breaking rocks. In case of the geological soft rock condition, as the rocks deforms so much, for example the Yacambu Tunnel of Venezuela, that the surrounding rocks deformation reaches as high as 20cm per minute. The severe deformation is supposed to destabilize the heading, causing the fault of the cutter head. The cutter head will also get stuck and even threaten the personal security [7-9] of constructors and operators in case of soft-hard interphase rocks, breaking strata or insufficient support as well as rock or mud eruption in a large area due to some extreme geological conditions, such as karst, flooded coal-bearing stratum and gas outburst. Besides, the low precision of the position & pose measurement and difficulties in controlling and correcting the position & pose measurement due to strong vibration, the tunnel axis deviates, which has brought great challenges to the design of the cutter head, power transmission and measuring and controlling system.

To avoid the cutter head getting stuck, it is necessary to take the following measures:

1. As for the soft rock stratum, it is feasible to over-excavate to reserve more space for the rock deformation or increase the hydraulic cylinder thrust properly to get the TBM cross the soft rock stratum as quickly as possible;

2. To enhance the design of the entire structure of the TBM, for example, tapering off the diameters of the shield of the cutter head;

3. As the current TBM is unable to percept the complicated geological conditions and the parameters for boring probed by artificial experiences hardly ensure the adaptability to the geological conditions, the measuring and controlling system of the TBM shall be improved and enhanced to detect abnormal stratum timely to avoid the extreme accidents like gas explosion and rock burst;

4. In most occasions, that the cutter head gets stuck is generally attributed to quick shift into the super-hard stratum with the torque not ready for this situation, so, increasing the TBM breakout torque is also a key point for the TBM cutter head breakout system in the future.

Driving Mode of TBM Cutter Head

At present, the TBM cutter head drive system has three driving modes which are double-speed motor drive, hydraulic motor drive and variable-speed motor drive.
Double-Speed Motor

The typical representative of this drive mode is Welter TB880E which we have imported for excavating the Qinling Mountain Tunnel. Its single drive unit is as shown as in the Figure 2 [2]. There are 3 groups in the Figure3 while in fact, there are 8 groups of drive motors and hydraulic motors in total. Its basic working principle is like this: The low speed high torque output from the disk-type friction clutch of the double-speed motor through the reduction gear is further decelerated after passing the pinion-girth gear pair system and transmitted to the cutter head to drive it to work. As the double-speed motor has two kinds of rotations, it also needs hydraulic motor as its auxiliary system of which the working principle is something similar with the double-speed motor drive.

![Figure 2. Structural representation of the TB880E single unit drive.](image_url)

1-Hydraulic motor, 2-Double-speed motor, 3-Coupling, 4-Disk-type friction clutch, 5-Brake, 6-Reduction gear

Figure 2. Structural representation of the TB880E single unit drive.

![Figure 3. Layout chart of the TB880E cutter head drive system.](image_url)
**Hydraulic Motor Drive**

The hydraulic motor drive is seldom used as main drive in the TBM mainly due to the power of the TBM cutter head drive system requiring for more than thousands of kW in general. In addition to that, problems like leakage and heating are also factors to lead great power losses and energy waste. Moreover, poor heat radiation underground fuels the pressure imposed on the auxiliary system, so it is quite rare to use the hydraulic motor alone. But as an auxiliary system, the hydraulic motor can play its best roll in the big speed-reducing ratio, large torque and good stability even at low speed [2].

**Variable-Speed Motor Drive**

Along with the development of variable-frequency technology, the variable-speed motor has started to become the main drive mode for the TBM. As its greatest advantage, it can regulate ‘synchronous speed’ by changing the frequency of the drive power supply so that the motor can output the torque large enough at any rotations to avoid the general motor from being damaged due to overcurrent of the coil when the torque is too large. The Figure 4 has shown a curve describing the rotation-torque characteristics within the frequency change range of 0~100Hz. In case of 0~50Hz, the correspondent synchronous rotation of the converter motor shall be 0~1200r/min which belongs to the constant voltage frequency ratio control, in this case, the maximum torque of the motor remains unchanged; in case of 50~100Hz, the variable-speed motor enters into the constant power zone and its maximum torque reduces gradually along with the rise of the rotation because of it being restricted by the maximum powers of the converter motor and the inverter [10-12].

![Figure 4. A curve describing the variable-speed motor rotation-torque characteristics.](image)

Compared with other drive modes, the variable-speed motor drive has many advantages: adaptable to different geological conditions with stepless speed change; start torque and breakout torque large enough to achieve breakout of the cutter head in a very short time; efficiency as high as more than 98%. The Figure 5 shows the variable-speed motor drive, of which the principle is similar to other drive modes only if the drive power turns into converter...
motor. The Figure 6 shows a curve describing the work status of the TBM cutter head with the variable-speed motor drive.

![Schematic diagram of variable-speed motor drive.](image1)

**Figure 5.** Schematic diagram of variable-speed motor drive.

![A curve describing the working status of the cutter head with the variable-speed motor drive.](image2)

**Figure 6.** A curve describing the working status of the cutter head with the variable-speed motor drive.

**Variable-Speed Motor + Constant Speed Motor Drive**

The variable-speed motor has a large torque, but sometimes it still fails in breakout of the stuck cutter head due to inadequate power, so it is necessary to achieve the breakout to improve construction efficiency by adding other auxiliary powers. The common auxiliary drive is to use the combination of variable-speed motor and constant speed motor drive, of which the basic features are as follows: the variable-speed motor works all the way during regular work and breakout so that the installed power can be made use of at its maximum; the breakout torque becomes more controllable and easier when the breakout torque transmitted from the constant speed motor to the cutter head can be adjusted by the thickness of the oil film of the liquid viscous clutch, which is as shown in the Figure 7.
Table 1 represents the comparison between the double-speed motor + hydraulic motor drive system and the variable-speed motor + constant speed motor drive system [3].

By the data shown in the table 1, the variable-speed motor + constant speed motor drive system is better than the double-speed motor + hydraulic motor drive system in the following aspects: the continuous speed regulation is available by adjusting the power frequency of the variable-speed motor according to different geological conditions so that the TBM becomes more adaptable; the breakout torque of the system increases by 49.2% by adding the constant speed motor as an auxiliary power for breakout so that the TBM is easier to achieve breakout than ever.

Table 1. Comparison between the two kinds of drive systems.

| Drive mode          | Double-speed motor + hydraulic motor | variable-speed motor + constant speed motor |
|---------------------|--------------------------------------|---------------------------------------------|
| Rotation            | 2.7r/min 5.4r/min                    | Constant torque 0~3r/min Constant power 3~6r/min |
| Rated torque        | Low speed 8791kN·m High speed 5789kN·m | Constant torque section: 9800kN·m Minimum value of the constant power section: 4900kN·m |
| Breakout torque     | 10503kN·m                             | 15668kN·m                                   |
| Installed power     | 3840kw                                | 3470kw                                      |

Key technology of the TBM cutter head drive system

As the core component of the TBM, the cutter head drive system is directly connected with the cutting capability as well as the boring efficiency and construction cost, having several key technologies as below to improve:
(1) Geological adaptability. The cutter head shall adjust the cutter head rotation and output torque timely according to the different geological conditions. At present, the variable-speed motor is a better choice for the geological adaptability.

(2) Breakout ability. The system shall restart itself and resume boring in a very short time in case of the cutter head getting stuck due to extreme working conditions. The variable-speed motor + constant speed motor drive system has improved the output torque of the system dramatically so far and yet other auxiliary systems need to be improved further so that more choices can be available.

(3) Cutting capability. It is mainly related to the drive ability of the cutter head. In order to make the cutter head penetrate into the rock in a very short time, crushing the rocks and expanding crushing zone with substantial power, the cutter head drive system shall provide larger instantaneous power.

(4) Cost control. The TBM consumes as high as thousands of kilowatts and the cost is hard to control due to low efficiency and huge waste in energy though there are many other drive modes like hydraulic drive. A more efficient drive mode will lower the cost for the construction by the TBM.

(5) Overexcavating function. In case of soft rock stratum, the problem of stuck cutter head due to the rock contractibility can be tackled by overexcavating. So a drive system with an overexcavating function will be more adaptable to all the soft rocks known as so far.

Conclusions

Looking back at the history of the TBM, the designers and manufacturers have always been pursuing any possibilities to improve the boring and breakout abilities of the cutter head drive system. Under the background of current technologies, as the main drive power, the converter motor which is adaptable to different geological conditions and has a strong cutting capability is a major development trend; the constant speed motor + liquid viscous clutch can make the cutter head output torque more controllable and provide larger instantaneous torque, playing a more important role in the breakout; with the variable-speed motor, the TBM can achieve the breakout in an easier way, which has a decisive significance in improving the construction efficiency and reducing the cost.

It is also no doubt that the new technologies emerging along with the innovations will bring new vitality to the TBM as well as brand-new concept to the construction.

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