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RESEARCH ARTICLE

Zhibin LIU, Haibo XIE, Huayong YANG

Simulation analysis of pressure regulation of hydraulic thrust system on a shield tunneling machine

Abstract Hydraulic thrust system is an important system in a shield tunneling machine. Pressure regulation of thrust cylinders is the most important function for thrust system during tunnel excavation. In this paper, a hydraulic thrust system is explained, and a corresponding simulation model is carried out in order to study the system characteristics. Pressure regulation of a certain group's cylinders has little influence on regulation of the other groups' cylinders. The influence will not affect the process much during tunnel excavation. Pump displacement may have a greater effect on pressure regulation and oil supply flow rate should be adaptive to the system's demand. A exacting situation is simulated to explain how pressure regulation works during tunnel excavation.

Keywords tunnel, hydraulic thrust system, pressure regulation, simulation

1 Introduction

A shield tunnel machine is a large and complex machine used in underground tunnel excavation. It is used in construction projects such as underground rail lines, urban pipelines, submarine tunnels, and so on. Hydraulic technique is widely applied in a shield tunneling machine. For instance, it is used in the thrust system, the cutter head drive system, the screw conveyor, and the segment erector.

Research works about tunnel excavation have been carried out. Sugimoto and Sramoon built a theoretical model for tunnel excavation based on mechanics analysis [1]; their simulation results are in good agreement with observed data [2]. Maynar and Rodriguez used a discrete numerical model to analyze the excavation process. Some studies about thrust force and torque were also carried out [3]. Xu et al. have discovered some relationship between working parameters during tunnel excavation [4]. Only a few studies about the hydraulic system on the machine have been done. Hu et al. have done some work on a thrust system of a machine. Pressure and flow compound control have also been researched [5].

A different system in Ref. [5] is studied in this research. Pressure regulation of thrust system is studied by using a simplified simulation model and cases of such regulation are discussed.

2 Thrust system

A thrust system is an important part of a shield tunneling machine. The system consists of power units (electric motor and hydraulic pump), hydraulic valves, and hydraulic cylinders as actuators. The number of thrust hydraulic cylinders is usually 16 or 32. If individual control of hydraulic cylinders is applied, a high number of proportional control valves and pressure sensors are required. Moreover, the machine operator has to control 16 or 32 pressure parameters during excavation. Individual control is rather complicated and expensive. Nowadays, thrust cylinders are usually divided into four or five groups, with the four-group arrangement more common. Four-group cylinders are divided into Group A, Group B, Group C, and Group D, corresponding to right zone, lower zone, left zone and upper zone. The proportion of A:B:C:D is usually 4:5:4:3, as shown in Fig. 1.

More cylinders are required in Group B so as to counter the weight of cutter head and the higher earth pressure in the lower zone. Oil pressures in different cylinders are the same if they are in the same group. In this case, only four proportional control valves are required, and the machine operator only has to control four pressure parameters. During tunnel excavation, hydraulic cylinders are supplied with high-pressure hydraulic oil, which exerts on the segments to generate a thrust force to push the machine

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Zhibin LIU, Haibo XIE (✉), Huayong YANG
State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China
E-mail: hbxie@zju.edu.cn

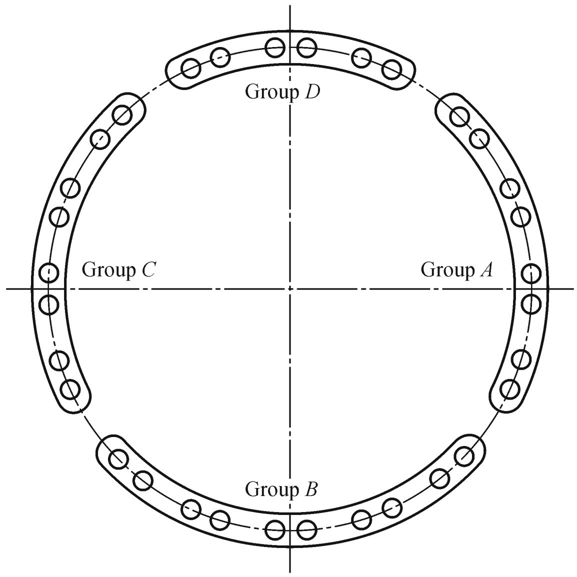

Fig. 1 Arrangement of 4-group hydraulic cylinders

forward. The machine operator may adjust hydraulic pressures of thrust cylinders to achieve steering control and machine posture adjustment. After a thrust process is over, segments will be installed to compose a new ring of tunnel. Meanwhile, thrust cylinders are retracted in order to make room for those segments. When a segment is located, corresponding cylinders are extended out. These cylinders exert on the segment, supporting the segment with a small force to complete the installation process.

3 Hydraulic circuit and modeling

The hydraulic circuit diagram for the thrust system is shown in Fig. 2. The system mainly consists of a variable displacement pump 1, a pressure relief valve 2, a directional control valve 3, four pressure reducing valves 4 and sixteen hydraulic cylinders 7. Pump displacement is proportional to the input signal. A pressure relief valve kicks into action when the system is overloaded, and a directional control valve is used to control the extension motion or retraction motion of cylinders. The pressure reducing valve is the most important component and is used to adjust the hydraulic pressure of the cylinders.

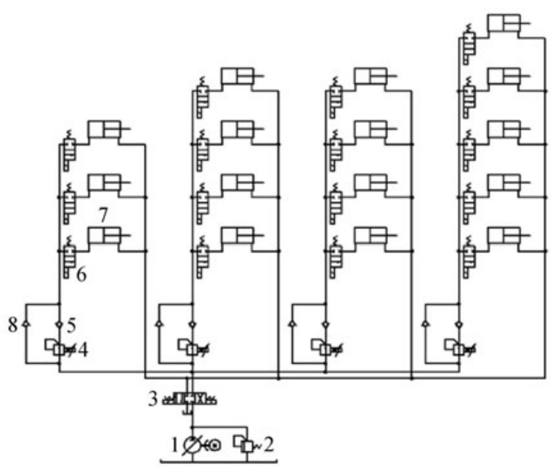

Fig. 2 Hydraulic circuit of thrust system

When the cylinder is extending, high-pressure oil comes from hydraulic pump 1, and then flows through directional control valve 3, pressure reducing valve 4, check valve 5, on/off valve 6, finally entering the rear chamber of hydraulic cylinder 7. The back pressure oil flows out of the rod chamber of cylinder 7, then through directional control valve 3 and back into the oil tank. When the cylinder is retracting, oil flows through directional control valve 3, then into the rod chamber of hydraulic cylinder 7. The back pressure oil flow out of the rear chamber, then through on/off valve 6, check valve 8, directional control valve 3, and finally into the oil tank.

Commercial software AMESim is used as the analysis tool for the simulation. To simplify the model, two groups of hydraulic cylinders (typically left zone and right zone) are considered for analysis. By using these two zones, it is possible to simulate the steering motion of the shield machine. The simulation model is shown as Fig. 3. All the hydraulic models are the normal models provided by the software except for the pressure reducing valves. The valve is built as a "super-component" by compositing several normal models. The valve gives more details about not only the working parameters but also the internal structures. A variable displacement pump is applied as proportional displacement control pump as it has the same function as that on a working shield machine. The pump displacement is proportional to the input signal.

Three kinds of forces are considered in the cylinder load model: earth pressure force, friction, and the force caused by the thrust motion. Earth pressure exerts on the cutter head and linings of the machine. The pressure force exerted on the cutter head affects the thrust motion, and the pressure force on the lining can be ignored. The friction force on linings of the machine caused by the earth pressure is considerable, accounting for about half or more of the thrust force. During excavation, however, the pressure force and friction force almost maintain constantly. Thus, these two forces are set as constant in the model. Earth pressure is set by the input signal of the load model, and friction is set in the mass model of cylinder. There is a linear relationship between advancing speed and thrust force, as shown in Fig. 4 [4]. The black star dots represent the experimental results for a 68% open ratio cutter head, and the white square dots represent the results for 36% open ratio. Each solid line shows the linear relationship between advancing speed and thrust force. The linear relationship has a good agreement with the observed data in construction of Line No. 3 in the Guangzhou Metro [6].

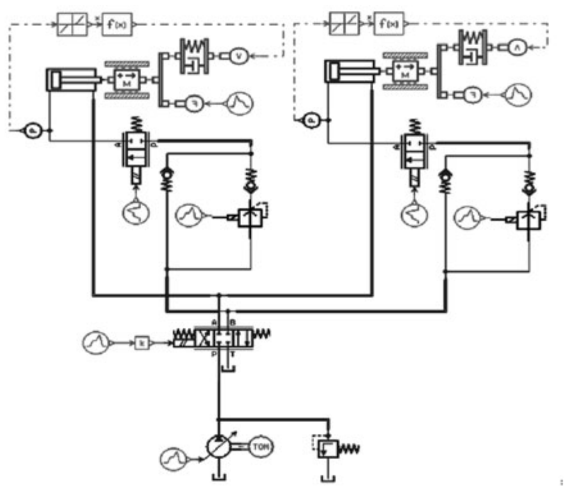

Fig. 3 Simulation model of the thrust system

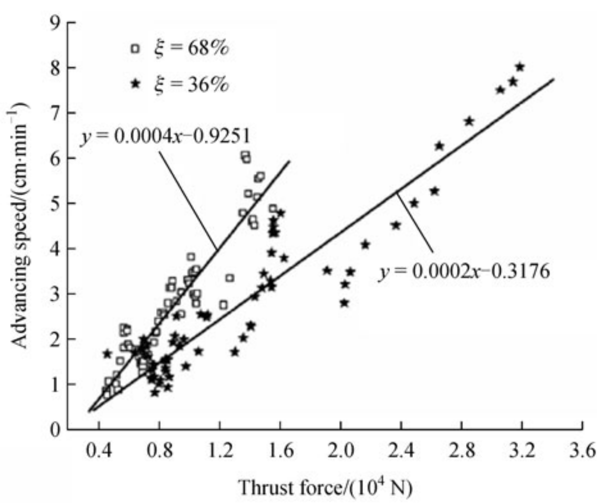

Fig. 4 Thrust force versus advancing speed in soft ground [4]

A greater thrust force causes a higher advancing speed. That is because greater force induces a greater feed rate of cutters, and more soil will be cut off in a fixed time interval. The thrust force should be greater than earth pressure exerted on the cutter head together with friction force on the lining, in order to push the machine to advance. If thrust force is not great enough, the machine will not advance. In Fig. 3, there is a dead band in the load model. The dead band represents the situation in which thrust force is not great enough to push the machine forward; such a situation is referred to in Ref. [6]. While the machine is advancing, an increase of the thrust force will cause an increase of advancing speed. This experiment result is applied to the load model. The orientation of machine advance is influenced by the pressure distribution of thrust cylinders so pressure regulation determines the procession of excavation. The machine operator may control the posture of the machine by adjusting the pressures of cylinder groups. The machine may steer left or right, or advance along a small angle of slope if corresponding settings of pressure regulation are given. Normally, at the end of a tunnel excavation, the difference between actual tunnel axis and designed tunnel axis should be no more than 20 mm. The machine operator will adjust the machine advancing axis to agree with the designed axis. As a result, pressure regulation is a very important function during tunnel excavation.

4 Simulation

The simulation parameters shown in Table 1 are obtained from a shield tunneling machine used in the construction of the Nanjing Metro. The left and right thrust groups are used for simulation, and sixteen hydraulic cylinders are reduced to eight. A 63 cc/rev maximum displacement pump should be reduced to 31.5 cc/rev. Piston diameter of a real cylinder is 300 mm, and rod diameter is 240 mm. Either the left or right thrust group, each of which contains four hydraulic cylinders, is simplified to one hydraulic cylinder, which has the same work area as the original cylinder group. As a result, the piston diameter and rod diameter of simulation cylinder are 600 and 480 mm, respectively. When oil pressure is about 8 MPa, which supplies about 9200 kN of thrust force, the machine begins to move. Reference [7] refers that friction force accounts for about 53.5%–73% of thrust force. Accordingly, friction force is set at 6000 kN, about 65% of thrust force. The remaining 3200 kN is exerted on the cutter head for tunnel excavation.

Table 1 Main simulation parameters

Item	Setting value
Pump maximum displacement	30 cc/rev
Relief pressure	35.3 MPa
Nominal pump speed	1500 rev
Piston diameter of cylinder	600 mm
Rod diameter of cylinder	480 mm
Force exerted on cutter head	3200 kN
Friction force	6000 kN

4.1 Pressure regulation

Steering control is simulated in this case. Both hydraulic cylinders are initially set to about 14 MPa. The machine advances straight and is expected to steer left. The pressure of right cylinder (P_{right}) should be higher than that of the left (P_{left}). P_{left} may maintain at 14 MPa. P_{right} is set to 20 MPa. Simulation result is shown in Figs. 5 and 6.

P_{right} is adjusted to 20 MPa as the step signal is given. There is a small overshoot of the pressure in Fig. 5 as there is a mass-spring system in the pilot stage. Overshoot of the

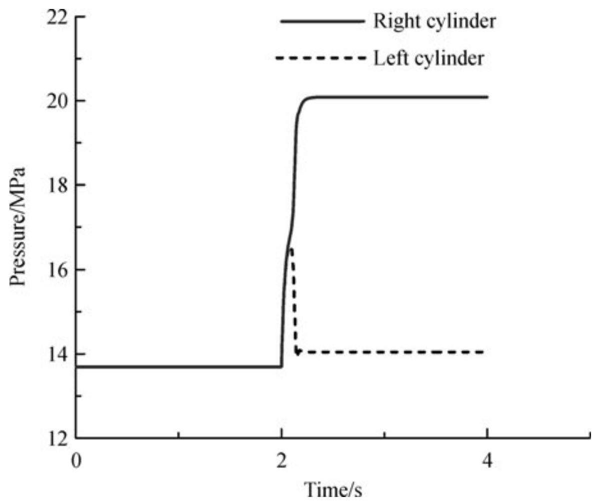

Fig. 5 Pressures of right and left cylinders during pressure regulation of left steering

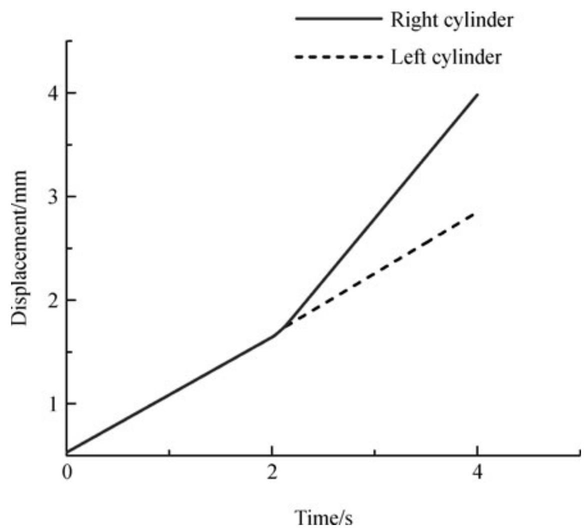

Fig. 6 Displacements of right and left cylinders during pressure regulation of left steering

mass-spring system causes overshoot of the outlet pressure in the main stage. P_{left} has a pulse when P_{right} is adjusted and increases slightly after adjustment. The sudden change in inlet pressure will cause the same pulse in outlet pressure at first.

Because the pilot stage frequency response is not high enough, when the pilot stage mechanism starts adjusting the valve's opening area, outlet pressure will decrease to the set value. The small increase of P_{left} might be caused by the increase of pump outlet flow rate. The pump outlet flow rate will be discussed next. This small difference in pressure will not affect the tunnel excavation. Higher advancing speed is achieved on the right side, as shown in Fig. 6. A left steering motion is carried out.

4.2 Pump displacement adjustment

Pump displacement should be adjusted when pressure regulation is carried out. Three cases are illuminated to explain the problem. Pressure regulation is operated as in the previous case.

Case 1: Displacement maintains at about 75% of maximum. The result is shown in Fig. 7.

P_{right} is adjusted to 20 MPa. Pressure regulation is achieved. However, pump outlet pressure is at 35.3 MPa, which means the system is overloaded and the pressure relief valve opens. Power loss caused by relief flow is considerable.

Case 2: Displacement maintains at about 50% of maximum. The result is shown in Fig. 8.

Pump outlet pressure is sensitive to the load pressure. There is no overload during pressure regulation. However, thrust pressure cannot be adjusted to 20 MPa because oil flow supply is not enough. Higher thrust pressure causes higher advancing speed, which means the cylinder requires more oil flow rate. Pressure regulation is invalidated in this case.

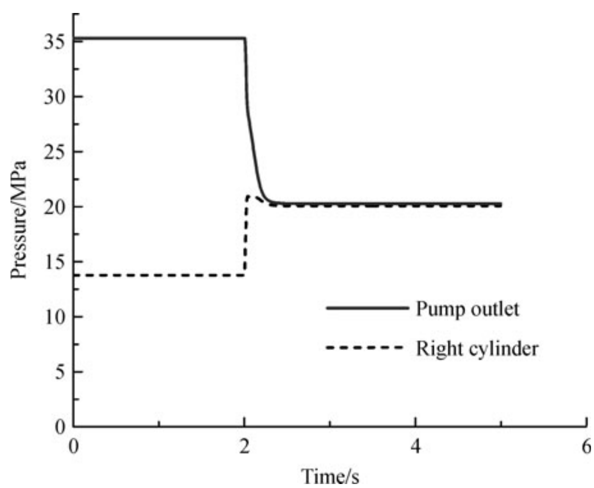

Fig. 7 Pressures of pump outlet and right cylinder when pump displacement maintains at 75% of maximum displacement

Case 3: Displacement is set at 50% at first, then 75% when pressure regulation is carried out. The result is shown in Fig. 9.

There is no overload. Pump outlet pressure is sensitive to the load pressure. Thrust pressure can be adjusted to 20 MPa. This is because pump displacement is adaptive to the system. A pressure regulation should be together with a pump displacement regulation.

4.3 A tough situation

In practice, an optimal tunnel project is worked out after considering commuters' needs, commercial demand, geological conditions, and so on. Shield tunneling machine is expected to advance in good geological conditions. Normally, a geological survey is done before the excavation process. It is impossible, however, to know everything

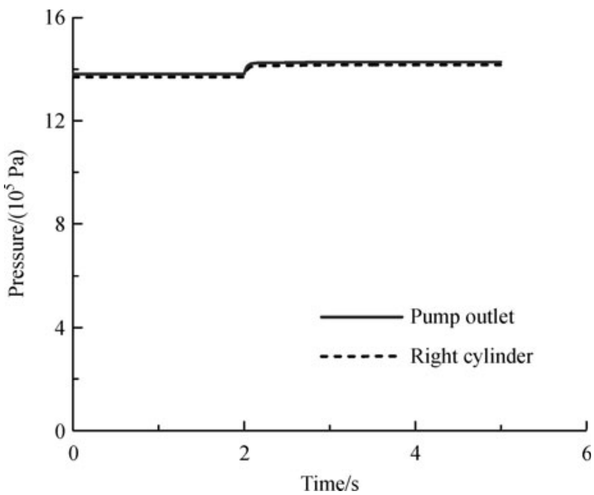

Fig. 8 Pressures of pump outlet and right cylinder when pump displacement maintains at 50% of maximum displacement

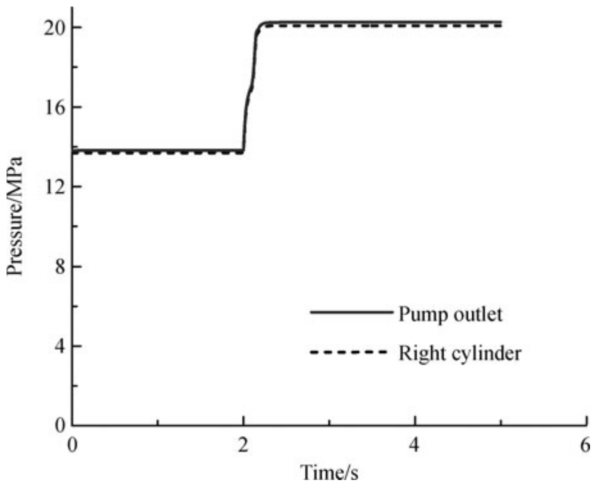

Fig. 9 Pressures of pump outlet and right cylinder when pump displacement is adjusted from 50% to 75% of maximum displacement when pressure regulation is applied

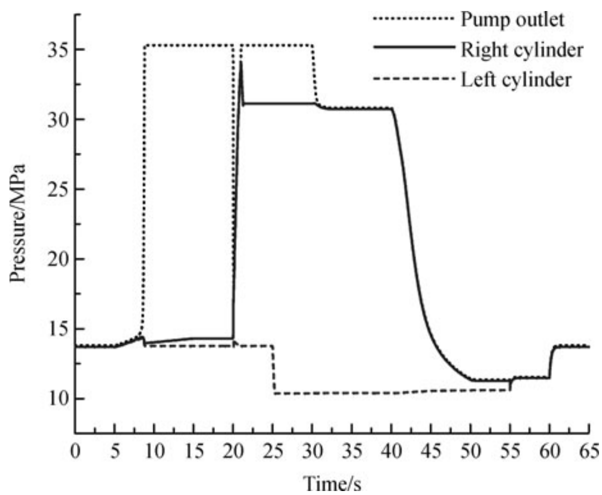

Fig. 10 Pressures of pump outlet, right cylinder, and left cylinder as the machine advances into and then out of some hard soil

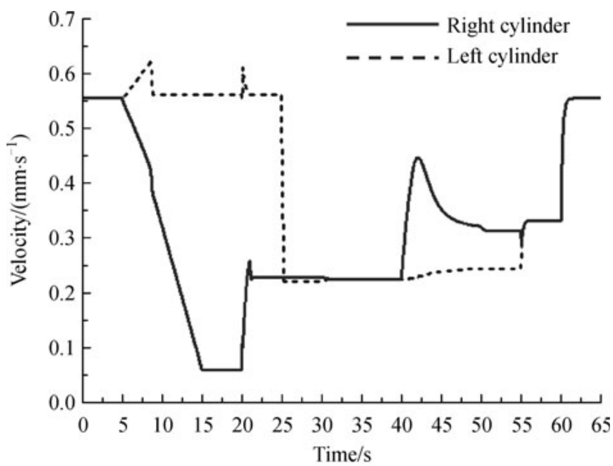

Fig. 11 Velocities of right cylinder and left cylinder as the machine advances into and then out of some hard soil

in the path of the machine. Unexpected conditions such as hard rock, wooden poles, quicksand or underground river may present themselves. In this study, we simulate such an exacting case, with the machine encountering some hard stratum on the right side. The following shows how the pressure regulation works and how the machine behaves. The simulation result is shown in Figs. 10 and 11.

Note: Time domain is used as x-axis in the simulation. However, time is not practical data. Time setting is artificial for the purpose of the illustration. Time period may be much longer in a real-world tunnelling process.

0–5 s: The machine is advancing straight in soft soil at normal speed. Thrust pressure is 14 MPa.

5–15 s: The machine is advancing from soft soil into hard soil on the right side. Right cylinder speed (V_{right}) decreases because P_{right} is not enough to maintain the normal speed. This causes surplus pump outlet flow rate and increase in system pressure. P_{left} and left cylinder speed (V_{left}) increase. System pressure increases until relief valve is open. Meanwhile, P_{left} and V_{left} drop to normal levels.

At 20 s: P_{right} is adjusted to 31 MPa. A pulse occurs in P_{left} and causes a pulse in V_{left}, as described before. Because an increase of flow rate occurs in right cylinder, flow rate of relief valve will decrease suddenly, causing a sudden drop in system pressure.

At 25 s: V_{left} should decrease to ensure straight advance. However, as V_{left} is higher than V_{right}, an unwanted right steering motion is carried out. Manual control is applied to decrease P_{left} until the machine advances straight.

At 30 s: Pump displacement is adjusted. After pressure regulation, the machine is now advancing at a lower speed. Pump displacement should decrease until overload is avoided, as over-adjustment will cause decrease of thrust pressure and advancing speed.

40–50 s: The machine is advancing out of the hard soil. P_{right} decreases as the machine goes into soft soil little by little. P_{right} is rather high at the beginning, which causes speed increases. Oil supply is not enough for the system anymore as V_{right} increases. This causes a drop in system pressure, and P_{right} decreases.

At 55 s: Thrust pressure is adjusted. Thrust pressure may be set to 14 MPa. Pressure regulation should take place before pump displacement adjustment. A slight increase of thrust speed happens due to the increase in thrust pressure. Oil supply is not enough, however, and pressure regulation is invalidated.

At 60 s: Pump displacement is adjusted. As pump displacement increases, thrust pressure is adjusted to 14 MPa and thrust speed increases. The machine is advancing at normal speed from now on. Of course, there is a little angle change of advancing orientation compared to the initial angle. The simulation is to show how the system behaves during the whole adjustment. If angle control is critical, angle feedback and steering control can be applied.

Adjustment usually takes place shortly after desynchronization. But in the simulation, adjustment takes place when the machine is "totally" advancing into hard stratum. The purpose is to find out what happens during the whole encounter, in other words, to find out the potential problem of the system.

5 Conclusions

Pressure regulation of the thrust system on a shield tunneling machine is studied in this paper. Pressure regulation includes two parts: pressure setting of thrust cylinders, and pump displacement adjustment.

1) Pressure regulation of one cylinder group may influence the pressures of the other groups. Increasing a certain group's pressure and pump outlet flow rate may cause small pressure increases in other groups. This small change in pressure is acceptable in tunnel excavation.

2) Pump displacement adjustment should be carried out when pressure regulation is applied. If pump outlet flow rate is more than the system demand, pressure regulation will also be achieved albeit with an unwanted pump pressure overload. If pump outlet flow rate is less than the system demand, pressure regulation is invalidated though pressure setting signal is given. Pressure regulation will be achieved as pump displacement increases enough.

3) A decrease of advancing speed may be a sign of encounter of hard soil. Compared with that, a decrease of thrust pressure may be a sign of encounter of soft soil. During excavation process, thrust pressure is set first, and then pump displacement adjustment should be carried out to finish the pressure regulation.

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