Research on the Soft-Starting Characteristics of Wet Clutches in TBM Cutter-Head Driving System

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Abstract. This article proposes to apply wet clutches to the cutter-head driving system of tunneling boring machine (TBM) and also investigates the soft-starting transmission characteristics of the wet clutch under three different strategies. The strategies discussed here refer to the engagement rules of plates in wet clutches, and they are: positive parabola, straight line, negative parabola. The numerical simulations corresponding to those strategies are carried out in the FLUENT, and the result indicates that the numerical method is valid for the good agreement with the analytical one. After comparing the simulation results, we conclude that the positive parabolic engagement strategy can be preferred during the soft-starting of TBM cutter-head if the invalid starting time, starting smoothness and heat dissipation are regarded as the evaluation standard.

Keywords: TBM · Wet clutches · Soft-starting strategy · FLUENT simulation

1 Introduction

The tunnel boring machine (TBM) is a kind of large complex equipment integrating mechanics and intelligent control. It is usually employed in many engineering fields, such as railway tunnel, highway tunnel, water conservancy and so on. However, some problems should also be paid more attention, especially for the lack of ability to escape when the cutter-head is trapped by the collapsed rock. If this happens, larger driving torque will be needed. What's more, more time will be wasted and economic losses are considerable. So how to help the TBM out becomes an engineering challenge.

According to the above problem, we propose a novel design for the cutter-head driving system. As we know, the cutter-head is justly driven by several variable-frequency motors in conventional driving system, so its maximum output torque cannot be changed once the manufacture of TBM is finished. Thus it will not help at all if larger torque is needed. However, the new design in Fig. 1 is definitely different. The wet clutches are applied to replace parts of variable-frequency motors in the original mechanical structure. When the TBM cutter-head runs normally, the wet clutches can work with the variable-frequency motors (Motor 2 in Fig. 1) synchronously. If the cutter-head is trapped, more separator and friction plates can be added to the wet

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clutches so that larger output torque will be obtained. So our research focuses on the working characteristics of wet clutches during the starting of head-cutter.

Wet clutches work through shear stresses of lubricant film and have a broad field in engineering application, such as belt conveyor, water pump, fans, cars, etc. As is shown in Fig. 1, when the pressure of control oil acting on the piston is increased, the separator plates will be pushed to the friction plates by the piston, and the thickness of the oil film between the plates will be smaller. As a result, the output torque of wet clutches will become larger based on the theory of hydro-viscous transmission, then the cutter-head will obtain larger power to help the TBM to continue working. This process is usually called soft-starting for wet clutches, and it can help cutter-head to start smoothly.

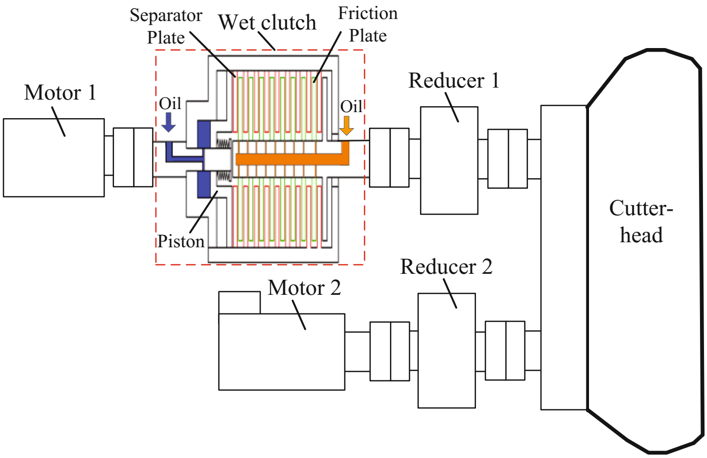


Fig. 1. The driving system of TBM cutter-head

In order to achieve a better understanding of the engagement process in wet clutches, many studies are launched. Andew M. Smith[1] focuses on the shearing mechanism of lubricant film in wet clutches. N.B. Naduvinamani et al.[2] devote themselves into the non-Newtonian fluid, and they not only establish mathematical models of squeeze Rabinowitsch fluid in circular stepped plates but also investigate the load-carrying capacity and response time. Mikael Holgerson[3] weakens the torque fluctuation and reduces the temperature rise of lubricant oil film by changing the normal force acting on the piston in wet clutches of cars. The squeezed lubricant film is studied through a numerical method by Khalid Zarbane[4], where some behaviors of squeezed film are observed and the results show that squeezing frequency and average film thickness can have an influence on the load-carrying capacity. M. Mahbubur Razzaque and Takahisa Kato[5] investigate many factors affecting the squeezing process under the isothermal and no slip boundary conditions. It is found that the angular orientation can significantly affect the squeezing process. Xie FW et al.[6] investigate the distribution and variation of the oil film temperature in hydro-viscous drive (HVD) by the means of simulation and experiment. It is showed that the temperature field will be affected by the grooves on the plates and parallelism of the working surfaces.

The rest of the paper is organized as follows. Section 2 introduces the axisymmetric physical model and three kinds of soft-starting strategies, and then the governing equations and their boundary conditions are described. The numerical simulations in the FLUENT are carried out in section 3, including physical parameter settings and the verification of numerical methods. And also the variations of film temperature and the output torques are analyzed and compared in this section. Finally some conclusions are drawn and future works are introduced.

2 Modeling

2.1 Soft-Starting Strategies

A simplified physical model with two parallel circular disks is shown in Fig. 2, and it is derived from the internal structure of wet clutch in Fig. 1. As is shown in Fig. 2, the input shaft and output shaft are fixed on the separator plate and friction plate respectively, and the two shafts are coaxial. The cylindrical polar coordinate system is used and the whole flow field is axisymmetric. The axis z coincides with axis of one shaft and the axis r lies on the working surface of friction plate. When the clearance between the two plates is filled with lubricant oil, the annular oil film forms and it has inner radius R_1, outer radius R_2 and thickness h. The separator plate without grooves can not only approach the friction plate with a velocity V (namely the growth rate of film thickness $-dh/dt$) along the axis z but also rotate around the axis z, while the friction plate can only rotate around the axis z. The temperatures of the two plates are T_f and T_s, respectively. The inlet temperature and inlet pressure of oil film are T_1 and p_1, and the outlet ones are T_2 and p_2. If the separator plate starts to rotate at an angular speed ω_1, it can drive the friction plate to rotate at an angular speed ω_2 relying on viscous shear stresses of oil film.

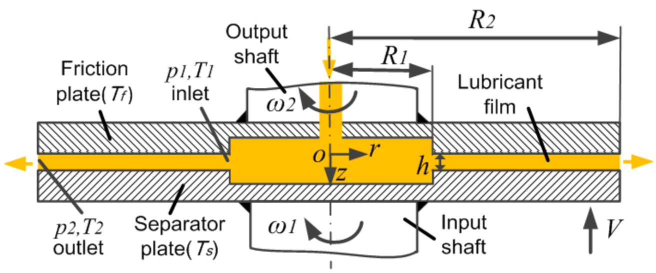


Fig. 2. Schematic drawing of a simplified wet clutch model

In order to find a better way to improve the dynamic working characteristics of cutter-head driving system during the soft-starting, the oil film thickness between two plates must be controlled well. The present study adopts three strategies for the variations of oil film thickness: positive parabolic strategy, linear strategy, negative parabolic strategy. They can be expressed as Eq. 1~Eq. 3. By the way, the ‘positive’ means that the coefficient of quadratic term is positive, and it is the same to ‘negative’.

$$h_{positive}(t) = a_1 t^2 + b_1 t + c_1, \quad 0 \le t \le t_0 \tag{1}$$

$$h_{linear}(t) = a_2 t + b_2, \quad 0 \le t \le t_0 \tag{2}$$

$$h_{negative}(t) = a_3 t^2 + b_3 t + c_3, \quad 0 \le t \le t_0 \tag{3}$$

where $a_1 > 0, a_2 < 0, a_3 < 0$. In our research, the total soft-starting time t_0 is set to 0.5s and the oil film thickness h decreases gradually from 0.2mm to 0.05mm during the time. Thus the unknown coefficients in Eq. 1~Eq. 3 can be solved with above settings and the equations are illustrated in Fig. 3. It is noteworthy that when the three strategies are tested respectively, their working conditions are kept the same, such as total starting time, initial and boundary conditions of oil film.

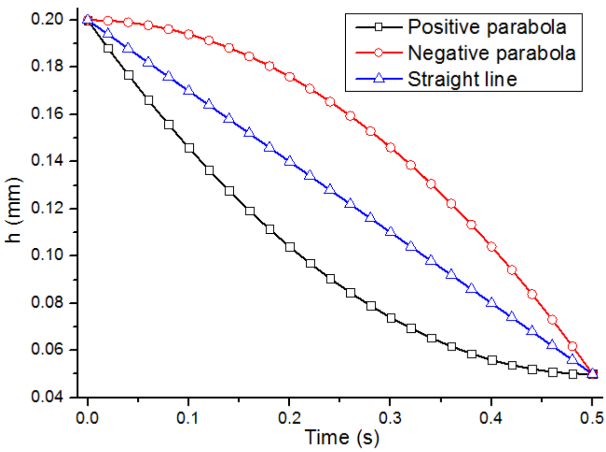


Fig. 3. Three kinds of variations of film thickness

In fact, what really should be concerned about is the growth rate of film thickness, namely the relative approaching velocity *V* (*-dh/dt*) of the two plates shown in Fig. 4. And we can conclude that the growth rate of film thickness is constant for the linear strategy, while the others’ vary linearly.

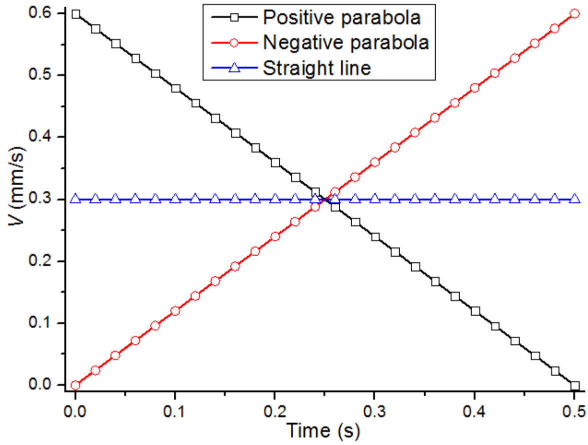


Fig. 4. Relative approaching velocity of the two plates

2.2 Governing Equations

In this paper, the lubricant flow between the plates is treated as Newtonian, laminar and axisymmetric. The mass forces and inertia effects are ignored, and the dynamic viscosity is assumed to be constant for small temperature rise. The film thickness is factually varying all the time during the engagement of wet clutches, so the soft-starting process is unsteady. Then the incompressible unsteady Navier-Stokes equations can be reduced as follows under the aforementioned assumptions and three ones in [7]:

$$\frac{\partial v_r}{\partial r}+\frac{v_r}{r}+\frac{\partial v_z}{\partial z}=0 \tag{4}$$

$$\rho\left[\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}\right]=-\frac{\partial p}{\partial r}+\mu\frac{\partial^2 v_r}{\partial z^2} \tag{5}$$

$$\rho\left[\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}+v_z\frac{\partial v_\theta}{\partial z}\right]=\mu\frac{\partial^2 v_\theta}{\partial z^2} \tag{6}$$

$$\frac{\partial p}{\partial z}=0 \tag{7}$$

which includes density ρ, dynamic viscosity μ and velocity components (v_r, v_θ, v_z) in the r, θ and z directions. For the sake of simplicity, the angular speed of the friction plate is set to zero, namely ω_2=0. Then the boundary conditions for velocity are concluded as follows:

$$v_r=0,\ v_\theta=0, v_z=0 \text{ at } z=0\,;$$
$$v_r=0,\ v_\theta=r\omega_1, v_z=V \text{ at } z=h(t)\,.$$

Because the outlet of the oil film contacts the atmosphere directly, the outlet pressure is zero, while the inlet pressure is kept constant p_0 by regulating the output pressure of pressure relief valve. Then the pressure boundary conditions can be expressed like that:

$$p = p_1 = p_0 \text{ at } r = R_1 ;$$
$$p = p_2 = 0 \text{ at } r = R_2 .$$

During the soft-starting process of TBM cutter-head, plenty of useless heat will generate due to the viscous shear stresses in lubricant oil. So the energy equation of the axisymmetric flow must be solved so that we can get a further knowledgement of the temperature variation of oil film. And the energy equation can be described by the following form based on the above assumptions:

$$\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z} = k \frac{\partial^2 T}{\partial z^2} + \mu \left[\left(\frac{\partial v_\theta}{\partial z} \right)^2 + \left(\frac{\partial v_r}{\partial z} \right)^2 \right] \tag{8}$$

where k is thermal conductivity and the second term on the right side represents the viscous dissipation. It has been verified that the condition ($T_s = T_f = T_1 =$ constant) can make the simulation results closer to the experimental results in [8], and that is still used in our research. So the temperature boundary conditions in axial and radial direction are:

$$T_s = T_{s0} \text{ at } z = h(t), \quad T_f = T_{f0} \text{ at } z = 0 ;$$
$$T_1 = T_{10} \text{ at } r = R_1, \quad T_2 = T_{20} \text{ at } r = R_2 .$$

where $T_{s0} = T_{f0} = T_{10} = \text{constant}$ and T_{20} is the atmosphere temperature, and they are all kept invariant.

3 Numerical Simulations in FLUENT

Before the soft-starting of cutter-head, the film thickness between plates in wet clutches will be kept at an appropriate value (namely initial film thickness h_0) under which the clutch cannot work at all. Then the input shaft will be driven by the motor at a desired speed ω_1. The engagement of plates will happen after the oil film is steady. So a steady simulation must be carried out firstly with invariant film thickness h_0 and the results will be regarded as the initial conditions of the unsteady process. After that, the three strategies can be employed respectively under the same initial conditions.

3.1 Methodology and Parameters

The 3D oil film model is meshed in the ICEM and then imported into the FLUENT where the numerical simulation is performed. The momentum equations in Section 2.2

are discretized by the finite volume method, while the energy equation is discretized through the second order upwind. The SIMPLEC algorithm is used to solve the discretized equations and the axial motion of friction plate is realized by programming user-defined functions (UDFs). Here are the physical parameters listed in Table 1.

Table 1. Physical parameters

Parameter	Value	Unit
R_1	0.06	m
R_2	0.1	m
T_{10}	303	K
T_{20}	298	K
T_{f0}	303	K
T_{s0}	303	K
ρ	872	Kg/m^3
M	0.0439	Pa • s
ω_1	1500	r/min
ω_2	0	r/min
h_0	0.2	mm

3.2 Verification

In order to verify the rationality of numerical method, the numerical solution of pressure will be compared with the analytical one. The simplified pressure equation can be derived from the generated Reynolds' equation[9], and it is as follows:

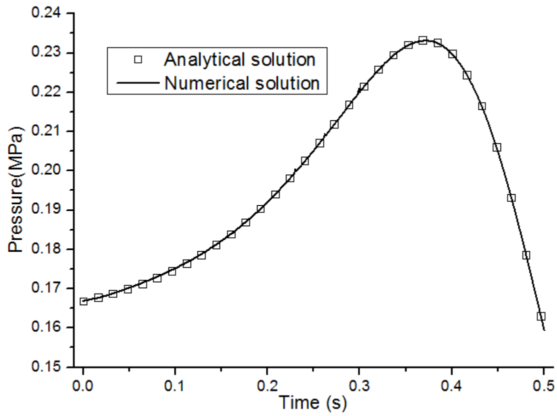
$$h^3 \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = \frac{3}{5}\rho h^3 \omega_1^2 + 12\mu \frac{dh}{dt} \tag{9}$$

Then the analytical equation of pressure will be obtained by integrating Eq. 9 with respect to r from R_1 to r twice, and the result can be gotten if taking the pressure boundary conditions into account:

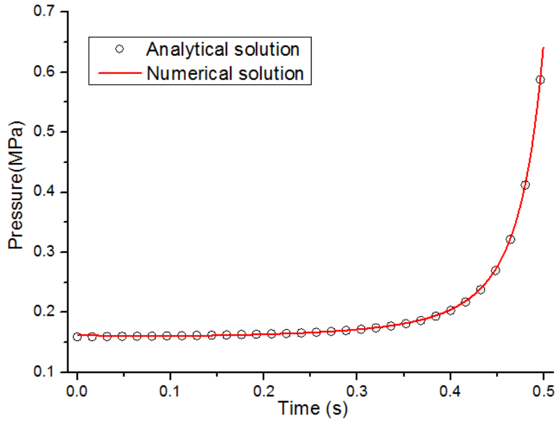
$$p = \frac{1}{4}K(r^2 - R_2^2) + C_1 \ln\frac{r}{R_2} \tag{10}$$

where $C_1 = [p_1 - \frac{1}{4}K(R_1^2 - R_2^2)]/\ln\frac{R_1}{R_2}$, $K = \frac{3}{5}\rho\omega_1^2 + \frac{12\mu}{h^3}\frac{dh}{dt}$.

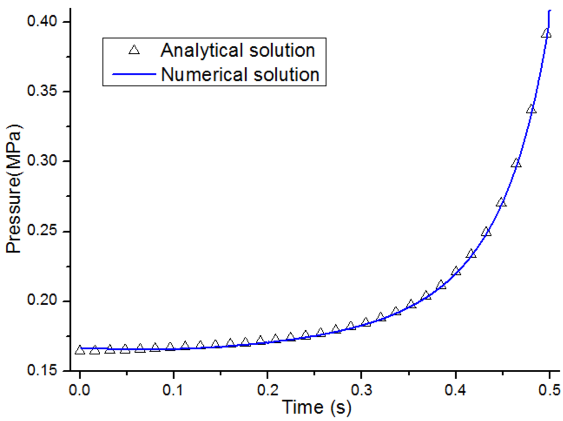
The numerical and analytical pressure solutions under different strategies, at r =76mm for example, are shown in Fig. 5. The results indicate that the numerical solutions coincide with the analytical one well, which confirms the numerical method is right. Furthermore, we can find that the film pressure can vary with the change of oil film thickness, which will induce different load-carrying capacity of wet clutches.



a. Positive parabolic strategy



b. Negative parabolic strategy



c. Linear strategy

Fig. 5. Numerical and analytical solutions of film pressure（r =76mm）

3.3 Comparison of Results

Comparison and Analysis of Temperature. The average temperature variations of the whole lubricant film corresponding to the three engagement strategies are shown in Fig. 6.

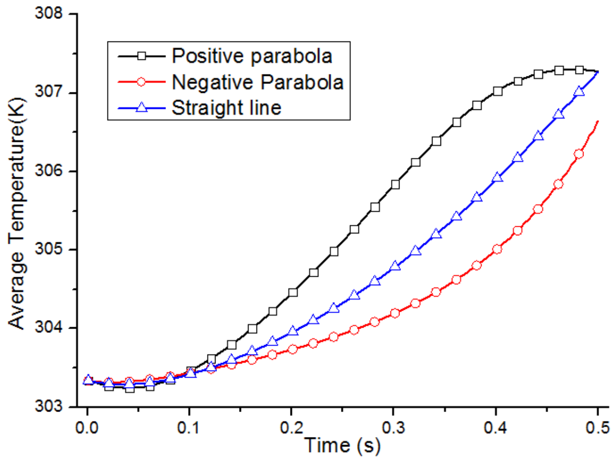


Fig. 6. Average temperature variations of the whole film

For the positive parabolic strategy, the temperature variation can be divided into two stages shown in Fig. 6. The temperature growth rate is rising all the time before 0.3s and reaches the maximum value at 0.3s. After this moment, the growth rate begins to fall until the soft-starting ends at 0.5s. The Fig. 4 has shown that the axial velocity of separator plate about this strategy decreases all the time from the maximum value 0.6mm/s to zero, but the axial velocities still stay at large values in the first part of starting time, so the growth rate of average temperature keeps rising during this period of time. However, with the further reduction of axial velocity, the temperature will rise slowly and even begin to fall from 0.46s. The proper explanation is that the growth of heat becomes less than the loss of heat which can be brought out by the lubricant oil.

While the average temperatures of flow field corresponding to the other two strategies keep increasing all the time. And the relative approaching velocity of the two plates stays at a lower level at the beginning time for the negative parabolic strategy, so its temperature also stays at a lower level before 0.25s, but the temperature rises rapidly from about 0.4s due to the larger axial velocity of separator plate. However, this process can often accumulate lots of heat in a short time, which can result in the plates' thermal deformation or burnout.

Different from the above two strategies, the temperature rise under the linear strategy is much steadier to some extent and this may own to its invariant engagement velocity.

Furthermore, the Fig. 7 illustrates the temperature variations of the annular oil film under positive parabolic strategy at different moments. We can find that the trend of temperature variation on one section of oil film is similar to the average trend, and the temperature rise will become larger with the increase of the radius.

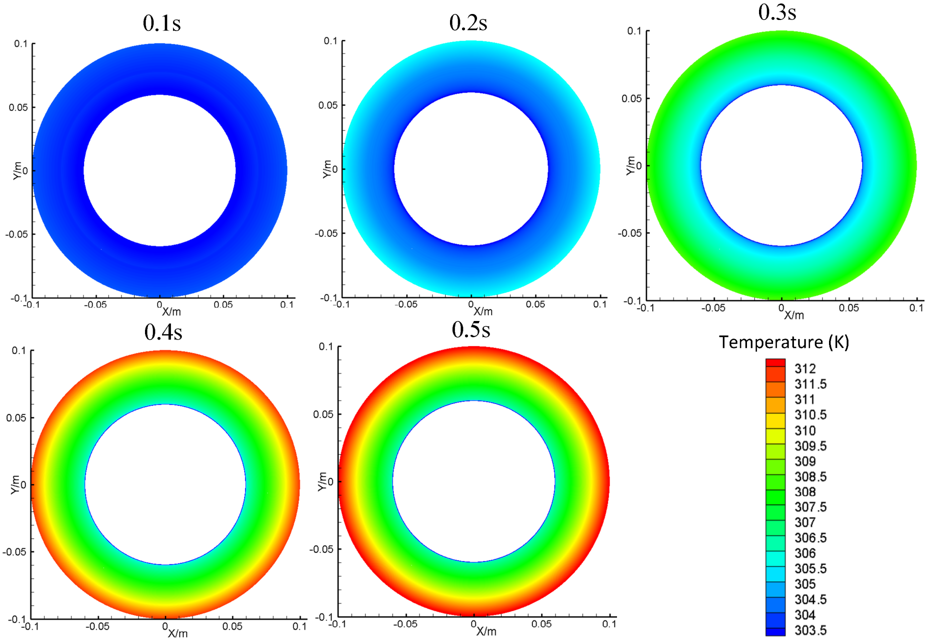


Fig. 7. Temperature variations of positive parabolic engagement at z=0.03mm

Comparing the temperature variations of three kinds of engagements, the positive parabolic strategy or linear one will be preferred. The results of linear strategy (which has constant engagement velocity) have indicated that the temperature of the oil film will rise with the reduction of film thickness, and more heat will generate during this period. So it is significant for the separator plate to slow down or keep a slow speed when the oil film becomes smaller and smaller, such that more heat will be brought out without damaging the plates.

Comparison and Analysis of Torque. The variations of viscous torque acting on the friction plate are illustrated in Fig. 8 and their growth rates are in Fig. 9.

In the practical application of wet clutches, the starting time during which the output torque is less than 30% of the required maximum value is defined as the invalid starting time. So the shorter the invalid starting time is, the higher soft-starting efficiency the TBM cutter-head driving system will obtain. We can find that the three strategies almost have the same maximum torques 18N·m in Fig. 8, which may result from the same oil film thickness at 0.5s. The invalid output torque can be calculated as about 6N·m based on the above definition. Thus for negative parabolic strategy, the invalid starting time is the longest lasting for approximately 0.3s, while the positive parabolic one has the shortest lasting for 0.12s and the linear strategy has 0.18s. Obviously, the positive parabolic strategy can promote the soft-starting transmission efficiency.

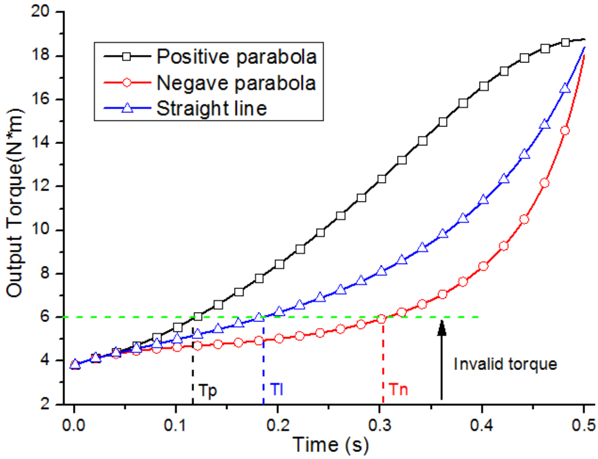


Fig. 8. Output torque of friction plate

However, the outlet torque increases sharply after 0.4s for the negative parabolic engagement, which means the cutter-head will be truly started from 0.4s and it is contrary to the fundamental idea of soft-starting due to the short starting time. Relatively speaking, the output torque variations of the other two strategies increase more steadily than the negative parabolic one during soft-starting.

The growth rate of output torque of the positive parabolic strategy in Fig. 9 can be divided into two stages: growing to the maximum value 44.5N·m/s and then falling to 2.0N·m/s gradually. That is to say, the output torque of wet clutches rises rapidly before 0.35s and rises slowly from 0.35s to the end. Moreover, we can also find that its growth rate of output torque stays at the highest level among the three during the time of 0~0.38s. However, the growth rates of output torques for both negative parabola and straight line are growing with time. The one of negative parabolic strategy rises most slowly before 0.4s and the rises sharply from about 0.42s, while the linear strategy grows smoothly by contrast.

For the soft-starting of TBM cutter-head driving system, it is preferred that the output torque grows quickly in the beginning time and then grows slowly before the ending time. This process can help to reduce invalid starting time and avoid wasting more power, moreover it can also help to keep the output torque vary smoothly before the soft-starting finishes. In conclusion, the positive parabolic engagement strategy is the perfect one absolutely at this point, and the mechanical driving system of TBM can start smoothly and suffer less from rigid impact with it.

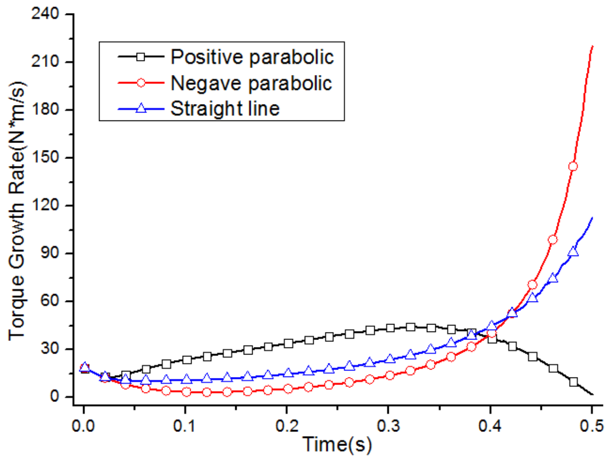


Fig. 9. Growth rate of output torque

4 Conclusions

The oil film behaviors and soft-starting transmission characteristics of wet clutches applied in TBM cutter-head driving system are studied under different soft-starting controlling strategies. On one hand, the positive parabolic engagement strategy has the highest soft-starting efficiency due to its shortest invalid starting time, and it can also help the cutter-head start smoothly. On the other hand, the negative parabolic engagement can produce a large temperature growth rate in a short time, which may burnout the plates due to heat accumulation, while the other two strategies have smaller temperature rises. In summary, the positive parabolic engagement strategy is the excellent way for the soft-starting of TBM cutter-head driving system. In our future work, the stabilities of transmission during the soft-starting of cutter-head will be treated as the key point, such as whether the turbulent flow can occur in oil film and how to control it.

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