The Vibration Analysis of TBM Tunnelling Parameters Based on Dynamic Model

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Abstract. In TBM tunneling process, the excessive vibration often leads to serious damage in some of TBM main components. Appropriate tunneling parameters such as cutterhead rotation speed, advancing speed, etc have a significant influence on TBM vibration. This study is based on a TBM muti-degree of freedom nonlinear dynamic model. The total force in three direction and torque on cutterhead are calculated according to the real data. The subsequent calculation shows that keeping the rotation speed in the range of 5.88–6.2 rpm can make the cutterhead vibration at a low level. And the effect of different TBM advancing speed is analyzed under this appropriate rotation speed. It shows that there is no significant change in the axial and vertical vibration condition of cutterhead and main frame with the advancing speed changing from 2–3.2 m/h but the horizontal vibration obviously increases. The deviation analysis of TBM motor's input torque is also carried out. The vibration situation of each pinion is analyzed which determines No 7,8,9 pinions are particularly affected.

Keywords: TBM · Coupled dynamics · Rotation speed · Advancing speed · Input torque deviation

1 Introduction

In hard rock condition, the construction process with big torque, thrust and large impact load. The excessive vibration of TBM will cause non-normal damage in critical component and shorten the life of TBM [1]-[2]. In the actual tunneling process, the driver often selected tunneling parameters based on experience and this may lead to accident. Therefore, theoretical analysis of the tunneling parameters that affect TBM vibration is of great important. It can determine a reliable range for the driver and deeper the diver's understanding about these tunneling parameters.

This paper analyzed TBM vibrations situation from the angle of dynamics. The excessive vibration will not only affect the excavation efficiency but shorten the fatigue life of structural component and lead to the accident [3]. Therefore, many scholars started studying the vibration dynamical characteristics of TBM. K.Z.Zhang [4]-[6] et al established a coupling dynamical model of shield machine considering redundant drive system, hydraulic propulsion system, geological conditions, etc, and the dynamical characteristics of the rotary system was studied based on the dynamical

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model. J.X.Lin and W.Sun [7] established a nonlinear dynamical model of cutterhead system, and analyzed the dynamical characteristics of cutterhead.

Many kinds of TBM dynamic models have been established by domestic and foreign scholars. This paper choose a dynamic model that comprehensively [8] considers time-varying impact load, a multi-component complex relationship between each component from cutters to gripper shoe. This paper analyzes some tunneling parameters such as advancing speed and cutterhead rotation speed that affect TBM vibration which provides theoretical basis for the actual construction.

2 Dynamic Model of TBM

The dynamic calculation in this paper is based on this dynamic model below. Firstly, the major components of TBM are show in fig. 1. TBM mainly includes cutterhead system and propel system. The cutterhead system includes cutterhead, bull gear, pinion, coupling, variable frequency motor, planetary reducer, etc. The propel system includes main frame, support cylinder and gripper shoe. The X, Y, Z represent horizontal, vertical and axial direction as shown in Figure 1.

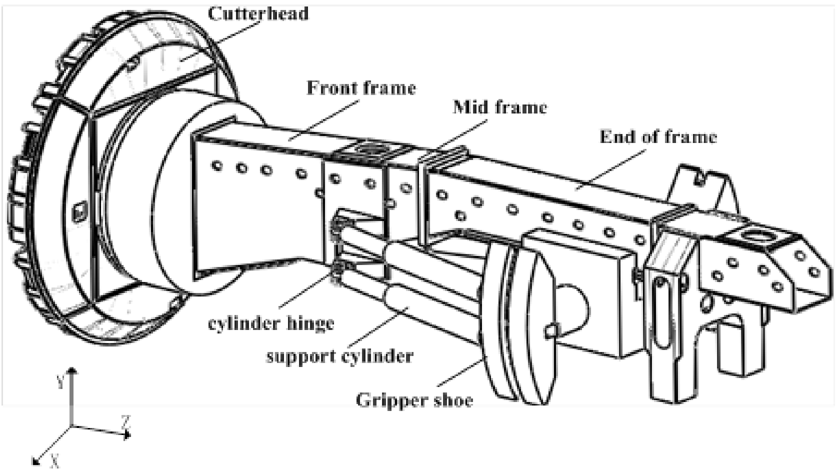
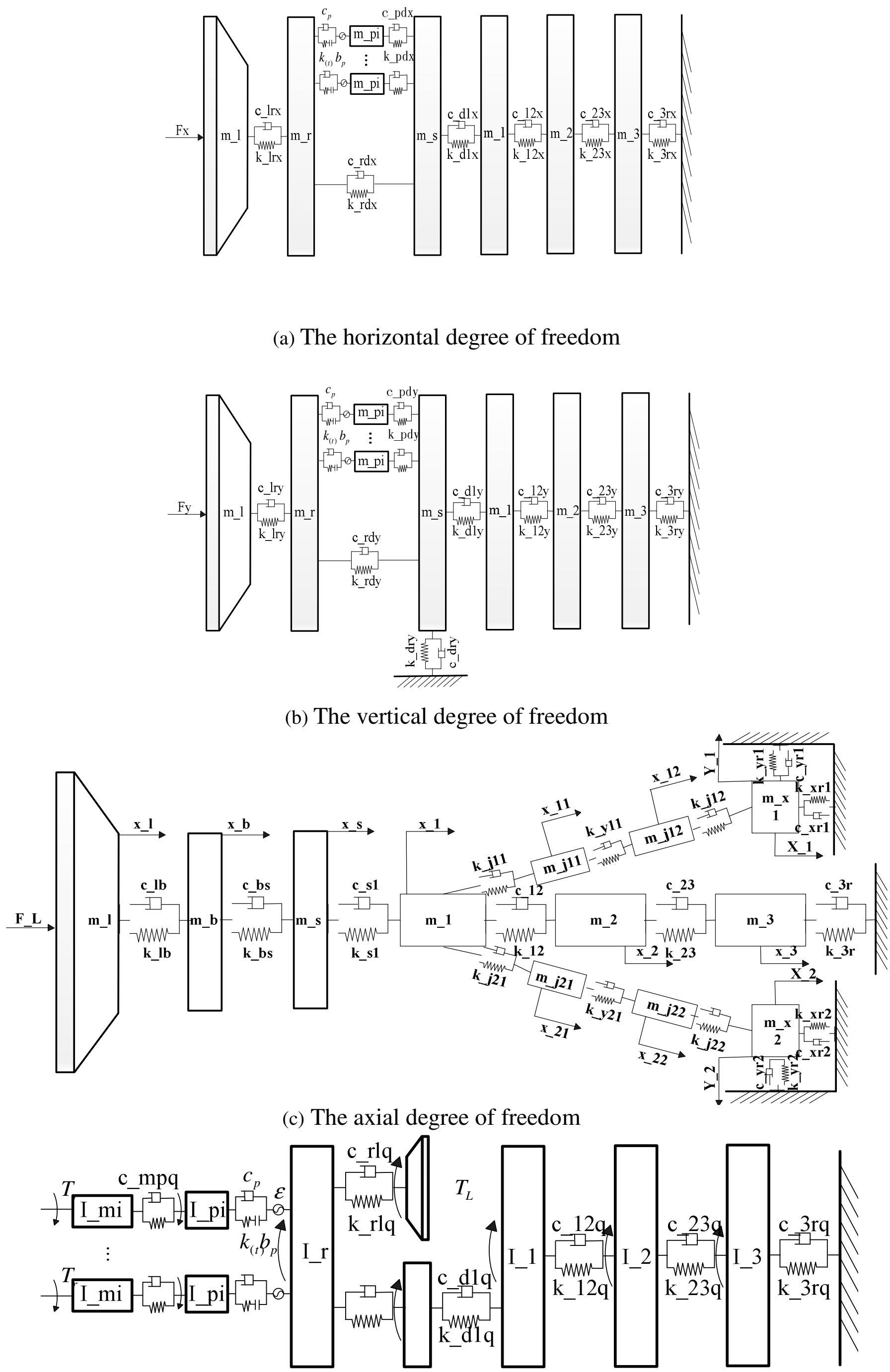


Fig. 1. The component diagram of TBM



(a) The horizontal degree of freedom

(b) The vertical degree of freedom

(c) The axial degree of freedom

(d) The torsional degree of freedom

Fig. 2. The dynamic model of TBM

where $m_l, m_b, m_s, m_1, m_2, m_3, m_r, m_{pi}$ represent the mass of cutterhead, cutterhead bearing, cutterhead support, front frame, mid frame, end of frame, bull gear and each pinion. $m_{j11}, m_{j12}, m_{j21}, m_{j22}$ represent the mass of 4 hinges as shown in Figure 3 (c). m_{x1}, m_{x2} represent the mass of 2 gripper shoes as shown in Figure 3 (c). I_{mi}、I_{pi}、I_r、I_l represent the rotary inertia of each motor, each pinion, bull gear and cutterhead. k_{j11}、k_{j12}、k_{j21}、k_{j22} represent 4 stiffness of the corresponding hinges. k_{xr1}、k_{yr1}、k_{xr2}、k_{yr2} represent the horizontal and axial support stiffness of the corresponding gripper shoes. k_{lb}、k_{bs}、k_{s1}、k_{12}、k_{23}、k_{3r} represent the structural stiffness of cutterhead, cutterhead bearing, cutterhead support, front frame, mid frame, end of frame. k_{lrx}、k_{rdx}、k_{pdx}、k_{d1x}、k_{12x}、k_{23x}、k_{3rx} represent the horizontal structural stiffness of cutterhead, bull gear, cutterhead support, front frame, mid frame and end of frame. k_{lry}、k_{rdy}、k_{pdy}、k_{d1y}、k_{12y}、k_{23y}、k_{3ry} represent the vertical structural stiffness of cutterhead, bull gear, cutterhead support, front frame, mid frame and end of frame. k_{mpq}、k_{rlq}、k_{d1q}、k_{12q}、k_{23q}、k_{3rq}、$k(t)$ represent the torsional stiffness of transmission shaft, cutterhead, front frame, mid frame, end of frame and the time-varying damping stiffness. T_L、T_{pi}、F_x、F_y、F_L represent the load torque on cutterhead, the input torque of motor, the horizontal unbalanced force on cutterhead, the vertical unbalanced force on cutterhead and the axial force on cutterhead.

The above nonlinear simultaneous equations can be expressed in matrix form:

$$M\ddot{X} + C\dot{X} + KX = F$$

where C、K represent the total damping matrix and stiffness matrix, F represents the force vector, X represents the displacement vector, and M represents the mass matrix. These simultaneous equations are solved by Newmark method.

3 The Analysis of TBM Tunneling Parameters

This paper takes the Robbins TBM in Liaoning northwest project as example. The tunneling parameters and cutthead parameters are shown in Table 1.

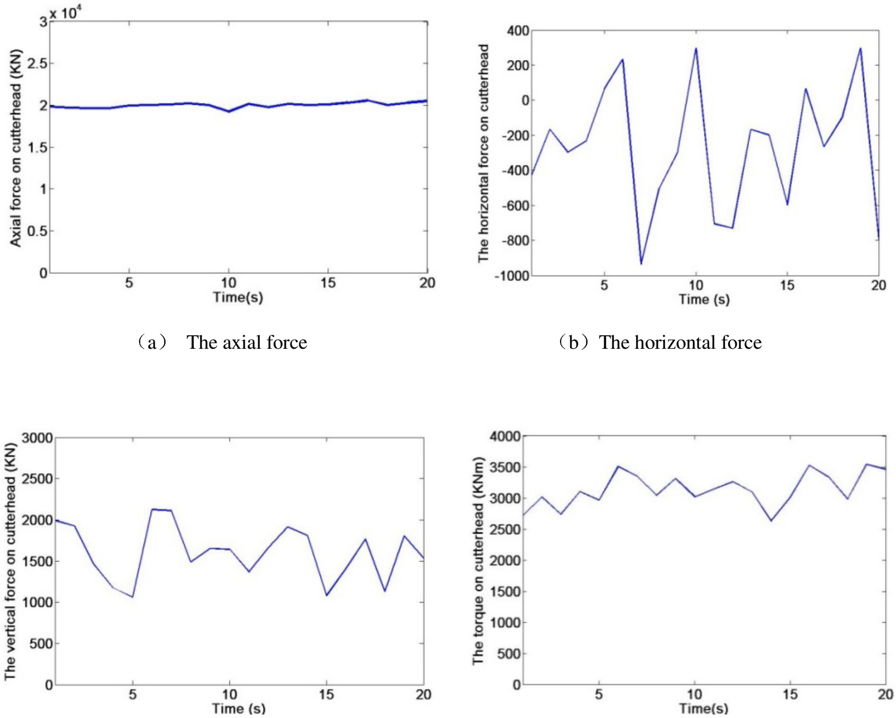
Table 1. The tunneling parameters and cutthead parameters

Tunneling parameters		Cutthead parameters	
Advance speed	2.4m/h	Diameter of cutterhead	8.53m
Penetration	7.8mm/rev	Mass of cutterhead	152t
Rotating speed	5.18RPM	Teeth number of bull gear	174
Rock mechanical parameters		Teeth number of pinion	14
Compressive strength	93.6MPa	Number of center cutter	8
Tunnel depth	130-1000m	Number of inner cutter	40
Confining pressure	6-30MPa	Number of gauge cutter	12
		Cutter spacing	75mm

In the process of actual excavation, the computer in master control room will record the TBM tunneling parameters such as the total thrust, the motor output torque, the pressure of side support cylinder, etc. The axial force, horizontal force, vertical force and torque on cutterhead which are used as external incentives when calculating the dynamic model are estimated based on the output parameters above. The loads under different advancing speed and rotate speed are intercepted as the input parameters and the more suitable tunneling parameters are determined comparing the vibration condition of TBM main parts in three direction. Due to the complicated situation in actual excavation, the actual advancing speed always fluctuate from 2 to 3m/h, and the rotate speed change from 2.5 to 6.7 rpm. It's hard to obtain the corresponding load with only one parameter changing. In analysis, the TBM advance speed is considered relatively constant, and the appropriate cutterhead rotate speed is found out firstly. Then effect of different advancing speed on TBM vibration is studied according to the optimal rotate speed.

3.1 The Optimization of Cutterhead Rotate Speed

The advancing speed fluctuates in the range from 2-3m/h in the field data segment, and different rotation speed corresponding data segments are intercepted. These data segments are taken as input load for calculating, and the vibration results of main components are obtained. Due to the random characteristic of these data segments, the data is intercepted in a non-equidistant way. Take the corresponding load when cutterhead rotation speed is 5.5 rpm as example. The axial,horizontal, vertical force and torque on cutterhead in 20 seconds are shown in Fig. 3.



（a） The axial force （b）The horizontal force

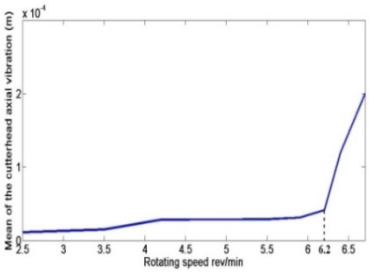
（c） The vertical force （d）The total torque

Fig. 3. The axial, horizontal, vertical force and torque on cutterhead

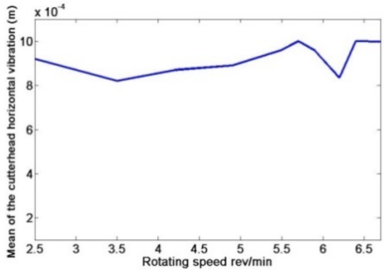
The non-equidistant rotation speed sequence is 2.5,3.5,4.2,4.9,5.5,5.7,5.9,6.2,6.4, 6.7rpm. The dynamic calculation is carried out according to the corresponding loads. The results are shown in Fig. 4.

It can be seen that the mean of cutterhead axial vibration increases slowly when the rotation speed is less than 6.2 rpm, and when the rotation, speed is larger than 6.2 rpm, the average axial vibration of cutterhead increases quickly. Thus for cutterhead axial vibration, keeping the rotation speed less than 6.2 rpm can effectively reduce the vibration. The cutterhead horizontal vibration does not change significantly with the increase of rotation speed. The cutthead vertical vibration obviously declines with the rotation speed increasing and drops to 60% of the original value when the rotation speed reaches to 5.88rpm. It’s worth noting that the vertical vibration increases after the speed reaches to around 6.5rpm.

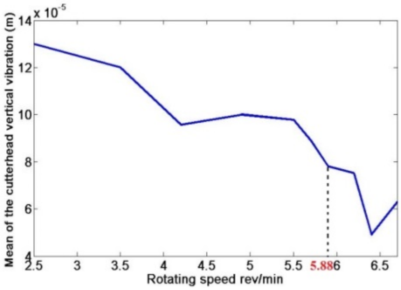
In conclusion, when the TBM advancing speed floats around 2-3m/h, keeping the parameter on the range of 5.88-6.2 rpm can make the cutterhead vibration at a low level. This may effectively reduce the TBM machine damage.



(a) The cutterhead axial vibration



(b) The cutterhead horizontal vibration

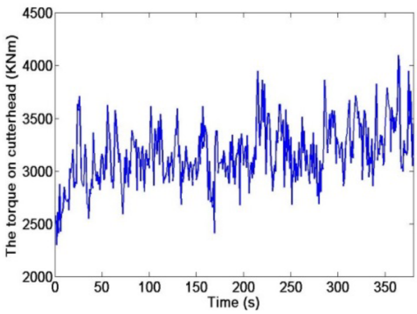


(c) The cutterhead vertical vibration

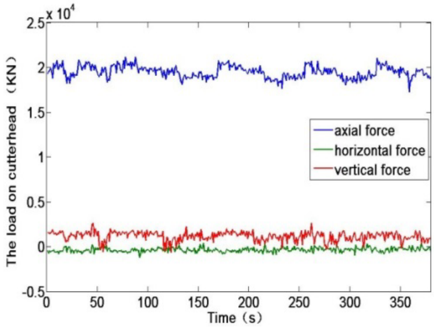
Fig. 4. The calculation results

3.2 The Analysis of Advancing Speed

Set the cutterhead rotation speed in the range of 5.88-6.2rpm, the data segment of advancing speed is 2, 2.2, 2.4, 2.6, 2.8, 3, 3.2m/hour, and each data segment length is 30s. The data is ascending ordered, the respectively cutterhead torque, axial, horizontal and vertical unbalanced force is shown in Fig. 5.



(a) The torque on cutterhead



(b) The unbalanced force on cutterhead

Fig. 5. The cutterhead torque, axial, horizontal and vertical unbalanced force

In the process of excavation, the advancing speed directly affects the propulsion cylinder time-varying stiffness. The calculation equation of the propulsion stiffness is listed below:

$$K_y(t) = K_y \cdot \cos\theta(t) \;\; \theta(t) = ac\tan\left(\frac{l_0 \cdot \sin\theta_0}{l_0 \cdot \cos\theta_0 + V_t \cdot t}\right)$$

where θ_0, l_0 represent the angle between the cylinder and main frame and the length of propulsion cylinder at the beginning of the excavation. V_t is the propulsion speed of cylinder and K_y is the cylinder support stiffness. With the advancing progress, the angle between cylinder and main frame decreases continuously, and the equivalent support stiffness changes correspondingly.

The analysis results are shown in Fig. 6.

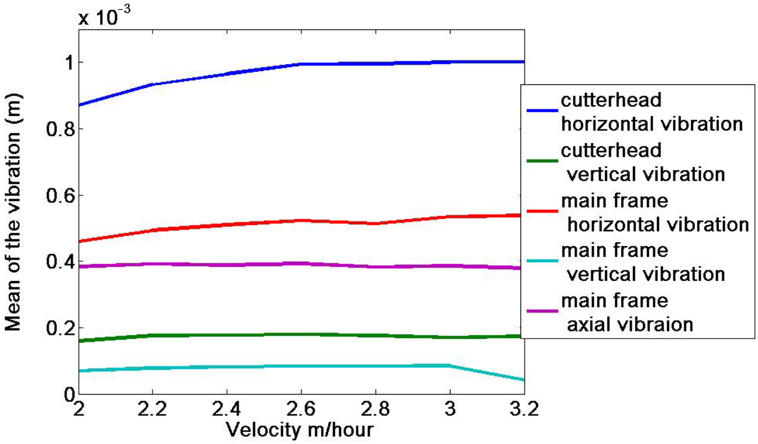


Fig. 6. The analysis results

It can be seen that there is no significant change in the axial and vertical vibration condition of cutterhead and main frame with the advancing speed changing from 2-3.2m/h. And the horizontal vibration of these two components increases. Specifically, the horizontal vibration of cutterhead increases by 14.9% while that of main frame increases by 16.9%.

4 The Deviation Analysis of TBM Motor's Input Torque

There were 10 parallel motors to input power for TBM, thus to drive the big gear ring to rotate. The phase layout of 10 motors was symmetrical in the right and left side, as shown in Fig 7. The respective phase angles were listed in Table 2.

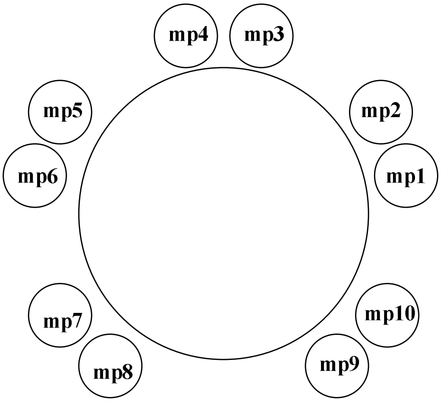


Fig. 7. The phase layout of 10 motors

Table 2. The respective phase angles

No.	1	2	3	4	5	6	7	8	9	10
Phase angle (°)	11.25	33.75	78.75	101.25	146.25	168.75	213.75	236.25	303.75	326.25

In actual project, due to the reasons such as gear assembly error, there would be certain error among the input torque of the motors. This kind of error would cause the change of the TBM vibration. Assume the total torque of the motors was T_{total}, the torque of every pinion was $10\% T_{total}$ when the input torque of every motor was the same. Under actual circumstances, assume the input torque of the gear which has the maximum torque was $(\Delta_{\max}\% + 10\%) \cdot T_{total}$, the input torque of the gear which has the minimum torque was $(\Delta 10\% - \Delta_{\min}\%) \cdot T_{total}$. The input error of the gear torque input error was defined as $w\%$.

$$w\% = \frac{(\Delta_{\max}\% + 10\%) \cdot T_{total} - (\Delta 10\% - \Delta_{\min}\%) \cdot T_{total}}{10\% T_{total}}$$

Take $w\%$ =10% as example, $\Delta_{\max}\% - \Delta_{\min}\% = 1\%$ from the equation above. The data set that the error was from 10% to 70% was studied. For each set, 10 torque between $(\Delta 10\% - \Delta_{\min}\%) \cdot T_{total}$ and $(\Delta_{\max}\% + 10\%) \cdot T_{total}$ were generated randomly. Meanwhile, the sum of the 10 pinion s' input torque was equal to the total torque, as shown in Table 3.

Table 3. The torque of each pinion under different input error

Error(%)	1(%)	2(%)	3(%)	4(%)	5(%)	6(%)	7(%)	8(%)	9(%)	10(%)
10	9.67	10.29	9.81	10.03	9.67	10.10	9.76	10.15	10.19	10.33
20	10.50	9.90	9.16	9.46	10.83	9.30	10.65	10.08	10.99	9.13
30	8.73	9.83	8.82	11.39	8.51	10.82	10.95	11.11	8.75	11.09
40	9.60	9.04	11.20	9.73	11.64	8.73	9.06	8.58	11.48	10.94
50	11.40	8.71	7.98	8.16	12.21	11.38	7.80	8.67	12.11	11.58
60	11.92	7.09	7.25	8.01	11.68	12.59	7.11	12.88	12.40	9.07
70	7.28	8.31	9.36	10.67	8.34	10.72	12.11	13.12	6.67	13.42

Take the input torque of every pinion as the input for the dynamic model. The changes of 10 pinions' average torsional vibration with the input error increases were shown in Fig. The changes of cutterhead and main frame's average horizontal-vertical vibration with the input error increases were shown in Fig. 8.

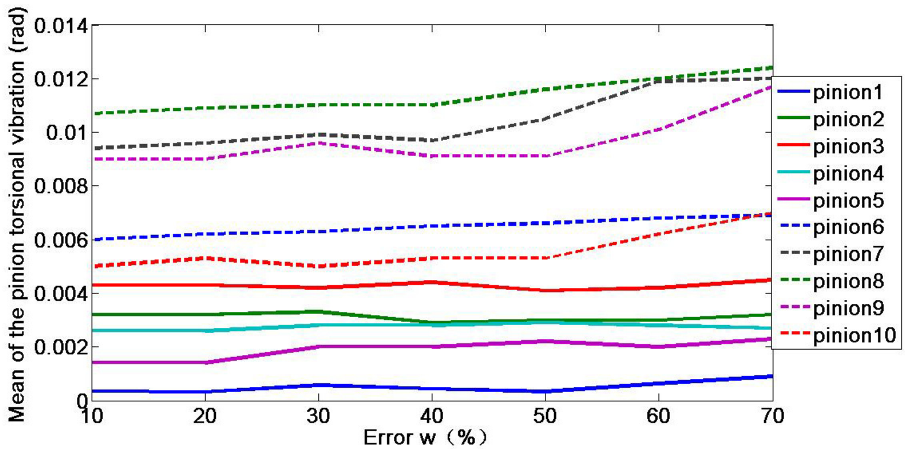


Fig. 8. The calculation results

Form the Fig above,

1. The No.7, No.8 and No.9 pinion has bigger torsional vibration which is in relatively tough vibration situation. This kind of situation may be related to the TBM's special pinion phase.
2. The vibration of No.1-No.5 pinion was small. Meanwhile, the change of the average vibration was not obvious as the input torque error increases.
3. The vibration situation of No.6-No.10 was relatively tough. The average vibration of No.6, No.8 and No.10 gear increased by 15.0%, 15.9%, 40.0% as the input error increases from 10% to 70%, and the process was approximately linear. The average vibration of No.7 gear increased by 27.7% as the input error increases from 10% to 70%. In particular, the average vibration increased by 22.7% as the input error

increases from 40% to 60%. The average vibration of No.9 gear increased by30.0% as the input error increases from 10% to 70%. Especially when the input error increases from 40% to 60%, the average vibration increased by 28.5% respectively.

It can be seem from the Fig. 9 that the pinion's input torque error affects cutterhead's average horizontal-vertical vibration significantly, but not obvious with main frame. The horizontal vibration of cutter increased by 7.9% as the input error increased from 10% to 70%. The increase of vertical vibration of cutterhead was 12.9%.

To sum up, the input torque error of the pinion had a significant effect on the overall vibration of the TBM. No.5-No.10 pinion's vibration increased with the growth of the torque error significantly.No.7 and No.9 pinion would have obvious vibration increment with small input error. For a major part of the TBM, especially for cutterhead, the growth of the pinion input torque error increased the horizontal-vertical vibration of the cutter evidently.

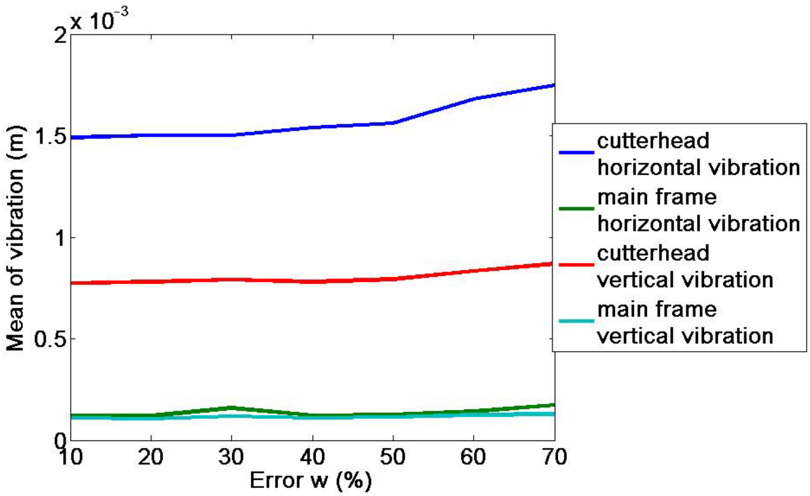


Fig. 9. The calculation results

5 Conclusion

In this paper, first hand real tunneling parameters are output and taken as input incentive for calculating a dynamic model. The suitable rotation speed is determined based on a TBM multi-degree dynamic model. The analysis results show that the rotation speed in the range of 5.88-6.2 rpm can make the cutterhead vibration at a low level. And the effect of different TBM advancing speed is analyzed under the appropriate rotation speed. It shows that there is no significant change in the axial and vertical vibration condition of cutterhead and main frame with the advancing speed changing from 2-3.2m/h but the horizontal vibration obviously increases. The horizontal vibration of cutterhead increases by 14.9% while that of main frame increases by 16.9%. In addition, the deviation analysis of TBM motor's input torque is also carried out. The analysis results show that the pinion vibration intensifies as the input error increases,especially for the pinion numbered 7,8,9. Meanwhile,the pinion's input torque error affects cutterhead's average horizontal-vertical vibration significantly which increases by 7.9% in horizontal direction and increases by 12.9% in vertical direction as the input error increased from 10% to 70%.

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