Study on Coupling Dynamics Theory and Simulation of Advance Support and Tunnel Surrounding Rock

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Keywords: Advanced support, Thin plate theory, Roof support, Surrounding rock coupling, Dynamics.

Abstract. In order to study the dynamic coupling problem of tunnel advance support equipment and surrounding rock, the roof dynamics model based on thin plate theory is established in this paper; advance support equipment is simplified, and the differential equations of motion of each component to establish the dynamic model of the whole; finally considering multi support conditions of advanced support roof system coupling dynamic model. The dynamic response of the coupling dynamic model under various working conditions is studied by using multi-body system dynamics simulation software RecurDyn. Through simulation we get the advance support top beam and retaining plate in dynamic response of collateral roadway conditions. The research conclusions of this paper can provide a theoretical basis for the research and design of advance support equipment in fully mechanized roadway.

Introduction

Advance support in comprehensive mechanized driving tunnel belongs to temporary support equipment for fully mechanized working face. It is used with tunneling equipment and anchoring equipment together to protect the safety of tunneling construction personnel, to achieve parallel operation of tunneling, supporting and anchoring equipments. In literature[4-6] basic research is carried out in view of the interaction mechanism between advance support and surrounding rock, and the design of advance support structure and strength check. The static and dynamic characteristics are analyzed by using finite element software ANSYS. In literature[7], the fuzzy PID control algorithm is used to study the support force of advance support. Taking minimum disturbance on the roof as control target, the control system of supporting force in stepping transition process is researched in literature[8]. Taking lifting efficiency and minimum disturbance on the roof control target, the electro hydraulic servo position and compound control method of advance support pressure is studied in literature[9]. In literature [9], the multi-cylinder synchronous control method of advance support is studied. In this paper, based on the roof dynamics model of the thin plate theory, considering multi support condition, the coupling dynamic model of the advance support and roof system is established, and the dynamic response of the coupled dynamic model is studied by simulation.

Roof Dynamics Model Based on Thin Plate Theory

Based on the elastic thin plate theory, the differential equation of forced vibration is:

\[ \nabla^4 w + m \ddot{w} w / D \dddot{t} = q / D \]

(1)

\[ \nabla^4 = \frac{\partial^4}{\partial x^4} + 2 \frac{\partial^2}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4} \]

\[ D = Eh^3 / 12(1 - \nu^2) \]

\( D \): Bending stiffness of roof board
\( E \): Young's modulus of elasticity
\( \nu \): Poisson ratio
\( h \): Roof board thickness
Foundation of Advance Support Dynamic Model

A simplified model of advance support dynamics is shown in figure 1:

Generalized displacement of top beam and columns at joint points in vertical direction:

\[
x_{55} = x_6 - \frac{1}{2}a \theta + b \psi; \quad x_{77} = x_8 - \frac{1}{2}a \theta - c \psi
\]

Generalized velocity of top beam and columns at joint points in vertical direction:

\[
\dot{x}_{55} = \dot{x}_6 - \frac{1}{2}a \theta + b \psi; \quad \dot{x}_{77} = \dot{x}_8 - \frac{1}{2}a \theta - c \psi
\]

Dynamic differential equations of the systems in advance support are:

Differential equation of the vertical motion of the balance jack piston rod on the lower left of beam 1:

\[
m_1 \ddot{x}_5 = k_1 (x_6 - x_5) + c_1 (\dot{x}_5 - \dot{x}_6) - k_2 \left( x_7 - \left( x_8 - \frac{1}{2}a \theta + b \psi \right) \right) - c_2 \left( \dot{x}_7 - \left( \dot{x}_8 - \frac{1}{2}a \theta + b \psi \right) \right)
\]

Vertical motion differential equation of the balance jack hydraulic cylinder on the lower left of beam 1:

\[
m_1 \ddot{x}_1 = k_1 x_1 + c_1 \dot{x}_1 - k_2 (x_2 - x_1) - c_2 (\dot{x}_2 - \dot{x}_1)
\]

Vertical motion differential equation of the balance Jack piston rod on the lower right of beam 1:

\[
m_1 \ddot{x}_7 = k_1 (x_5 - x_7) + c_1 (\dot{x}_7 - \dot{x}_5) - k_2 \left( x_8 - \left( x_9 + \frac{1}{2}a \theta + b \psi \right) \right) - c_2 \left( \dot{x}_8 - \left( \dot{x}_9 + \frac{1}{2}a \theta + b \psi \right) \right)
\]

Vertical motion differential equation of the balance jack hydraulic cylinder on the lower right of beam 1:

\[
m_1 \ddot{x}_2 = k_1 x_2 + c_1 \dot{x}_2 - k_2 (x_3 - x_2) - c_2 (\dot{x}_3 - \dot{x}_2)
\]

Vertical motion differential equation of the balance Jack piston rod on the lower left of beam 1:

\[
m_1 \ddot{x}_6 = k_1 (x_5 - x_6) + c_1 (\dot{x}_6 - \dot{x}_5) - k_2 \left( x_7 - \left( x_8 - \frac{1}{2}a \theta - c \psi \right) \right) - c_2 \left( \dot{x}_7 - \left( \dot{x}_8 - \frac{1}{2}a \theta - c \psi \right) \right)
\]

Vertical motion differential equation of the balance jack hydraulic cylinder on the lower left of beam 2:
Vertical motion differential equation of the balance Jack piston rod on the lower right of beam 2:

\[ m_2 \ddot{x}_2 = k_4 x_2 + c_3 \dot{x}_2 - k_4 \left( x_3 - x_4 \right) - c_2 \left( \dot{x}_3 - \dot{x}_4 \right) \]  

(9)

Vertical motion differential equation of the balance jack hydraulic cylinder on the lower right of beam 1:

\[ m_2 \ddot{x}_2 = k_4 x_2 + c_3 \dot{x}_2 - k_4 \left( x_3 - x_4 \right) - c_2 \left( \dot{x}_3 - \dot{x}_4 \right) \]  

(11)

Top beam dynamics differential equation in the vertical direction:

\[
mx_1 + F_1(t) + F_2(t) + F_3(t) \left[ x_2 - \left( x_1 - \frac{1}{2}a\theta + by \right) \right] \cdots k \left( \dot{x}_2 - \left( \dot{x}_1 - \frac{1}{2}a\theta + by \right) \right) - c \left( \ddot{x}_2 - \left( \ddot{x}_1 - \frac{1}{2}a\theta + by \right) \right) 
\]  

(12)

\[ c_1, c_5 : \text{Contact damping coefficient of the piston rod and the cross beam of the balance jack.} \]  
[ \]  
\[ c_2, c_3, c_4 : \text{Contact damping coefficient of advance support column and base plate.} \]  
[ \]  
\[ k_1, k_6 : \text{Contact stiffness coefficient of the piston rod and the cross beam of the balance jack.} \]  
[ \]  
\[ k_4, k_5 : \text{Contact damping coefficient of advanced support column and base plate.} \]  
[ \]  
\[ k_L : \text{Equivalent stiffness of jack piston and hydraulic cylinder, which is determined according to the stress state of the hydraulic cylinder.} \]  
[ \]  
\[ m_1 : \text{Mass of piston rod.} \]  
[ \]  
\[ m_2 : \text{Mass of hydraulic cylinder.} \]  
[ \]  
\[ m : \text{Equivalent mass of beam.} \]  
[ \]  
\[ a : \text{Width of top beam.} \]  
[ \]  
\[ b : \text{Distance between top beam centroid and the front pillar.} \]  
[ \]  
\[ c : \text{Distance between top beam centroid and the back pillar.} \]  
[ \]  
\[ F_1(t), F_2(t), F_3(t), F_4(t) : \text{Outside excitation of advance support.} \]  
[ \]  

**Coupling Dynamic Model of Advance Support and Roof System**

The multi-point contact dynamic model of advance support and top plate is shown in Figure 2. Setting the coordinate system of longitudinal beam as \( xOy \), \( C \) is any point on the arched beam. It coordinates before deformation are \( C(x, w_0) \). The coordinates of arc length are \( S_0, w_0(x) \) is the coordinate function of axis line to the axis \( y \) before deformation. When the arch beam deforms under forces, the coordinates will be \( C'(x + u, w_0 + w_1) \), and the coordinates of arc length will be \( S_0' \). \( u \) is the displacement of the arched beam in the direction \( x \). \( w_1 \) is the displacement of the arched beam in the direction \( y \). So the following formulas can be derived.

\[
\frac{du}{dS_0} = \sqrt{(dx/dS_0 + du/dS_0)^2 + (dw_0/dS_0 + dw_1/dS_0)^2} \cos \theta - \cos \theta_0 
\]  

(13)

\[
\frac{dw}{dS_0} = \sqrt{(dx/dS_0 + du/dS_0)^2 + (dw_0/dS_0 + dw_1/dS_0)^2} \sin \theta - \sin \theta_0 
\]  

(14)

\[
\cos \theta_0 = \frac{dx}{dS_0}, \sin \theta_0 = \frac{dw_0}{dS_0} 
\]  

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Coupling Dynamics Simulation of Advance Support and Roof System

Coupling Model and Parameter Determination

The coupling dynamics of advance support equipment is studied by using multi-body system dynamics simulation software RecurDyn. The roof model grid is automatically meshed by using SOUD10 unit and mesh command attached in the software. Setting Set Patch of the flexible roof as passive contact surface and the longitudinal beam surface which contacts directly with the roof as Face Surface active contact surface, and setting the bottom of the support column as an elastic structure, the coupling dynamics model of advance support and roof system is shown in Figure 3.

![Figure 3. Coupling dynamics model of advance support and roof system.](image)

Through the Import command in RecurDyn, the advance support model is introduced into the simulation environment. The gravity acceleration in modeling environment is set as 9806.65 mm/s², the length and width of the background mesh as 100, Icon/marker size as 100 and the load of advance support - roof system as FORCOS (time, 0,75000010000).

Coupling Dynamics Simulation of Advance Support and Roof System

Coupling dynamic characteristics analysis of advance support side and top plate. The random load of advance support is simplified as harmonic load. Set load as 10000N, frequency as 7 Hz and simulation time as 25 s. The contact force between advance support equipment and the roof, the contact force between the side wall and the top plate, and the deformation of the side wall are shown in Figure 5.

![Figure 4. Node distribution of side help model.](image)  ![Figure 5. Contact force of side.](image)

Figure 6 shows the contact force between roof and 5 nodes selected from 5 sections. When the nodes and the roof contact stably, the maximum contact force appears at the nearest node 53558 from beam clamped edges and load fluctuation is the most, then the two nodes 53574、53563 near the support column. The minimum contact force appears at the farthest node 53369 from the support column and the contact force fluctuation is more stable.

Deformation characteristics of the side wall in different simulation time are shown in Figure 6. Figure 6(a) shows the deformation characteristics when simulation time is 7s. The side just contacts with the roof, support column of side reaches the initial support force and begins to bear the working resistance of the roof. During the supporting process, due to the pressure impact of the side to the roof, side self-vibration and disturbance in fully mechanized cutting process, side displacement deformation is much more intense. As shown in Figure 6(b), at the end of the simulation side displacement deformation is in a steady state. The deformation decreases relative to the initial contact state.
(2) Coupling dynamic characteristics analysis of the supporting beam and the roof
Select the nodes at the contacting point between the top damping body and the roof. The identifier is shown in Figure 7. The contact deformation characteristics of the top plate are shown in Figure 8.

Figure 8 shows the contact stress characteristics curve of 5 nodes selected in the first section. When the nodes and the roof has a stable contact, the contact force of the node 50328 at the contacting point between the roof and the damping body in top middle of advance support. The contact force fluctuation is the most volatile. Then the two nodes 50364, 50292 on both sides of the middle damping body. And the contact force of node 50364 is relative bigger than 50292, which means unbalance loading occurs on the roof. The contact forces of two nodes 50400 and 50273, which are a little farther from the middle damping body are relatively small.

Figure 9. Deformation characteristics of roof at different time.

Deformation characteristics of roof in different simulation time are shown in Figure 9. Figure 9 (a) shows the deformation characteristics when simulation time is 7 s. The advance support just contacts with the roof, the main and servicing support column reaches the initial support force and begins to bear the working resistance of the roof. During the supporting process, due to the pressure impact of advance support to the roof, roof self-vibration and disturbance in fully mechanized cutting process, roof displacement deformation is much more intense. As shown in Figure 9 (b), when the simulation time lasts, roof displacement deformation zone is in a steady state. The deformation decreases relative to the initial contact state. At this time, advance support is a stable state.

Conclusion
In this paper, the roof dynamic model is based on thin plate theory. A coupling dynamic model of advance support and roof system considering multi-support condition is established. Dynamic
responses of dynamic model in different working conditions are studied by simulation. The results show that due to the pressure impact of side to the roof, side self-vibration and disturbance in fully mechanized cutting process, side displacement deformation is very severe. Due to pressure impact of advance support to the roof, self-vibration, fully mechanized cutting disturbance, the roof displacement is very severe.

References


