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Dynamic modeling of gripper type hard rock tunnel boring machine

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ABSTRACT

A multi-system coupled closed-form dynamic model for controller design of hard rock Tunnel Boring Machine (TBM) is presented with consideration of the closed chain structure and interactions with rocks. Based on the analysis of closed chain structure, the motion equations of each rigid body in the TBM system are derived in terms of generalized coordinates. To obtain the mathematical model for controller design, the nonholonomic constraints are novelly proposed to describe the complex interactions between the TBM shield body and rocks instead of the traditional finite element method. With the nonholonomic constraints assumption, a closed-form mathematical model with Lagrangian multiplier is obtained by applying the Lagrangian approach. The interactions between the cutter-head and rocks as the main load acting on the TBM during excavation are described by the widely used Colorado School of Mines (CSM) model. The simulations of excavation performance of TBM in different distribution conditions of rocks with various UCS and TS are compared and discussed.

1. Introduction

Shield technology is a modern tunneling technology that contains a set of hydraulic, manufacturing, control, measurement techniques, which has become an important technology in the major underground excavation such as transportation, underground engineering, mining, water conservancy. With the development of technology, a kind of TBM equipped with automation control capability is needed. Though some computer-aided automatic control systems are used in TBMs (Du and Du, 2011), these systems are based on empirical methods without any knowledge of physical model of TBM. In addition, the present automatic control systems can't well adjust the snake-like motion back to the planned alignment (Sugimoto and Sramoon, 2002; Sramoon et al., 2002). Therefore, it is difficult to achieve good control performances with the pure empirical method. To solve such problems, a theoretical model for the automatic control that considers the entire structure of the TBM and the interaction between TBM and rocks is necessary. The TBM is mainly constituted by three core systems, which includes the cutter-head driving system, hydraulic thrust system, and gripper-carrier system, as shown in Fig. 1. The cutter-head system is driven by several motors as shown in Fig. 2. The hydraulic thrust system includes thrust cylinders and beams with parallel structure to increase the thrust forces. The gripper-carrier system is used not only to stabilize the TBM but also to adjust the TBM orientation following the tunnel excavation position by torque cylinders and gripper cylinder, as shown in Fig. 3. Considering the complex mechanical structure and highly coupled characteristics, the dynamic modeling of TBM is a challenging task.

Up to now, to evaluate the behavior of TBM, many papers about modeling of TBM have been published. Over past decades, the modeling of TBM can be divided into two categories: (a) the 3D finite element model, which means the structure and rocks are modeled with finite element method; (b) the mathematical model, which denotes that the behavior of TBM is described with mathematical analysis. Specially, Lee and Rowe (1990) first developed the 3D finite element model for shield tunneling. Swoboda and Abu-Krisha (1999) and Kasper and Meschke (2004) developed more comprehensive 3D finite element models of TBM through taking into account the ground conditions/components of equipments. However, these studies were developed in soft ground, which is much different from the condition in hard rock. As such, some researchers develop the 3D simulation model for TBM in hard rock (Zhao et al., 2012; Zhang et al., 2009), where the complex interaction between the rocks and the tunnel machine are considered. It should be noted that although the finite element model can work well on the behavior analysis of TBM, it can not be applicable for controller design. To solve this problem, the mathematical models of TBM are needed. Sugimoto and Sramoon (2002) and Sramoon et al. (2002) developed a theoretical model to predict the shield behavior without data recorded, in which sensitivity of model parameters were analyzed and the shield

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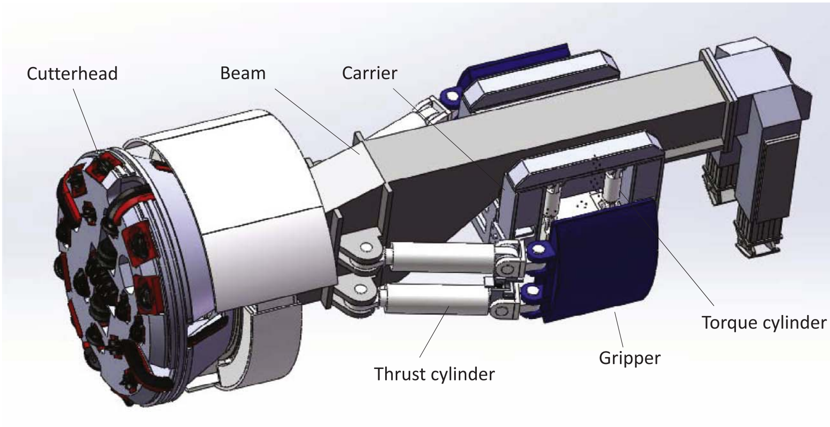

Fig. 1. Hard rock TBM.

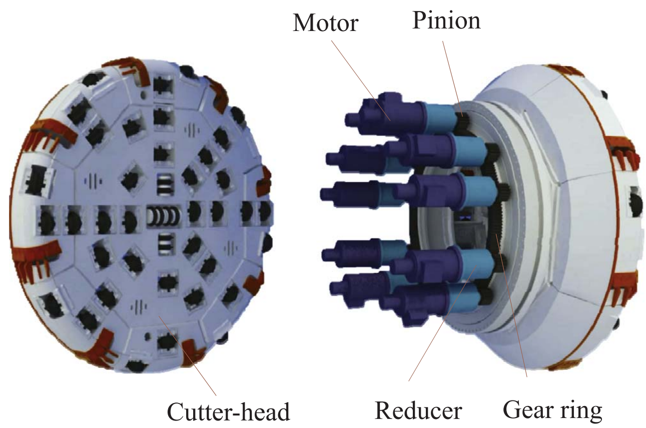

Fig. 2. Cutter-head driving system of Hard rock TBM (Xian et al., 2010).

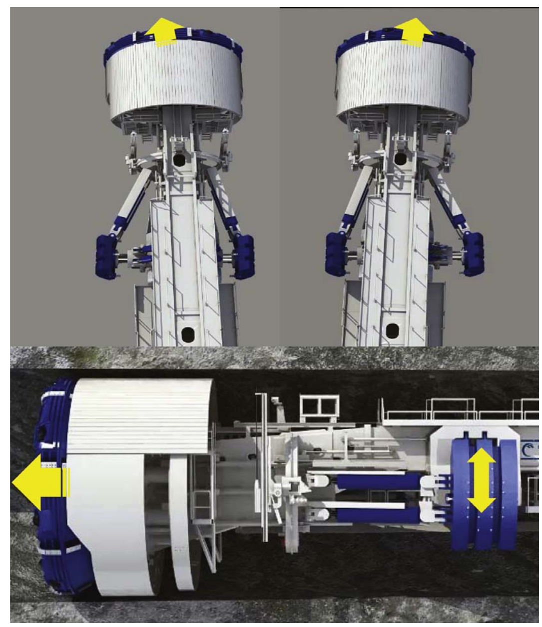

Fig. 3. Direction adjustment of Hard rock TBM.

behavior during excavation was obtained by solving equilibrium conditions of forces and moments based on the finite element method. Other investigators have made much effort on the theoretical model of TBM. Xian et al. (2010), Li et al. (2013), Huo et al. (2015), Sun et al. (2013), Zhang et al. (2010) and Ling et al. (2015) presented the general nonlinear time-varying dynamic models, in which different gear backlash, mesh damp and transmission error are taken into account, focusing on the dynamic model of cutter-head driving system.

In literature, much work has been carried out about the modeling of TBM by 3D finite element method or mathematical models for part of TBM system such as cutter-head driving system. However, seldom work has been done about the dynamic modeling for controller design of TBM including the thrust system and gripper-carrier system. In addition, the torque acting on the cutter-head from rocks can't be treated as disturbances, which is actually coupled with the thrust system. There are some models presented to describe the interaction between cutter-head and rocks (Rostami et al., 1996; Farrokh et al., 2012; Tóth et al., 2013; Gong and Zhao, 2009). Among them, the CSM model (Rostami et al., 1996) is the most widely used in actual applications.

In this paper, a new mathematical dynamic model including the cutter-head system, the thrust system and the gripper-carrier system of gripper type hard rock TBM is presented through considering the closed chain structure of thrust-gripper-carrier system of TBM (Harib and Srinivasan, 2003; Lopes, 2009) and the complex interactions with rocks. The kinematic model of TBM is carried out including the closed form expressions of the inverse Jacobian matrix of the mechanism and its time derivative. And the interactions between the TBM and rocks along the side directions are first proposed to be described as the nonholonomic constraints (Fierro and Lewis, 1995) instead of the finite element method. In addition, the CSM model is applied to describe the load acting on cutter-head.

2. Preliminaries

Let $O_W{-}X_WY_WZ_W$ be the world frame and $O_B{-}X_BY_BZ_B$ be the body fixed frame that is fixed at any point on the rigid body, as shown in Fig. 4. A generalized coordinate vector $\mathbf{q} = (x_p, y_p, z_p, \phi, \theta, \psi)^T$ is defined to describe the posture (i.e., pos and rotation) of the rigid body in which the RPY angles ϕ, θ and ψ are the orientation of the body fixed frame $O_B{-}X_BY_BZ_B$ with respect to the world frame $O_W{-}X_WY_WZ_W$ at time t. The mapping between the two frames is given by 3×3 rotation matrix ${}^W_B\mathbf{R}$ (Craig, 2005)

$$ {}^W_B\mathbf{R} = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi s\theta c\phi \\ s\psi c\theta & c\psi c\phi + s\psi s\theta s\phi & -c\psi s\phi + s\psi s\theta c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (1) $$

where c and s denote cosine and sine respectively. Consider the orthogonality and reciprocal characteristics of the rotation matrices ${}^W_B\mathbf{R}$ and ${}^W_B\mathbf{R}$ (Craig, 2005), the following relationship is satisfied.

$$ {}^W_B\mathbf{R} = {}^W_B\mathbf{R}^{-1} = {}^W_B\mathbf{R}^T \quad (2) $$

The angular velocity of the rigid body in the world frame can be