Automation in Construction 76 (2017) 97–107

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Dynamics research on grouping characteristics of a shield tunneling machine's thrust system

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 26 November 2016
Accepted 9 December 2016
Available online 11 January 2017

Keywords:
Shield tunneling machine
Dynamic force transmission
Grouping strategy
Thrust system

ABSTRACT

Grouped operation of a thrust system has a great effect on the performance of a shield tunneling machine. With consideration of the kinematic constraints from surrounding composite strata, the dynamic model of a grouped thrust system is firstly proposed to investigate the force transmission relationship between external resistances and driving forces. Then, the resistances model is derived based on the parametrized expression of two-layer composite strata. On the basis, the characteristics of each grouping mode for the thrust system are finally studied with variable geologic conditions by an index revealing the overload on segments. Results show that the contours of this index against impacting accelerations are a cluster of quasi-ellipses whose center can help to obtain the optimum grouping mode. Moreover, the adaptability of the thrust system to impacts will change significantly with the variations of the surrounding strata. These findings can serve as helpful instructions for the selection of grouping strategies in future tunneling projects.

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1. Introduction

The first successful implementation of Earth Pressure Balance (EPB) shield tunneling in Japan in late 1970s has led to the rapid development of this automated tunneling technique. Due to its higher working speed and better safety assurance, shield tunneling machine is now commonly used for tunnel constructions [1]. Recently, with the sharply increasing demand for urban underground infrastructures and public transportation systems such as metros and railways, the shield tunneling technique has become one of the most attractive research topics in the field of underground space technology. A typical shield tunneling machine is generally comprised of a cutter, a thrust device and segments [2]. The thrust device is the most important component for providing sufficient feeding force to cut soils and rocks, which is mainly composed of dozens of parallel-arranged hydraulic cylinders.

In tunneling projects, shield tunneling machines always work in a narrow workspace with high temperature, large gravels, etc. Hence, accurate performance analysis for a shield tunneling machine has become a primary investigation prior to a successful tunnel construction. At present, performance analysis based on statistical models is a most prevalent approach. Within these models [3–6], measured geologic parameters and performance parameters were correspondingly converted into a database to carry out regression analysis. The results were then used to predict the performance of the shield tunneling machine in the upcoming constructing section, together with initially detected geologic parameters. However, this technique regarded the performance analysis of a shield tunneling machine as a pure mathematical issue. The specific configurations for the thrust device of the machine and its interaction with the surrounding strata were ignored, which most likely led to constructing failures in tunneling along a curvilinear path, such as snake-like motion and being stuck.

Additionally, in order to reduce the complexity of operation and control in practical implementations, grouped-control scheme is always applied to the hydraulic thrust device of a shield tunneling machine [7]. Due to the fact that the resistant forces, the bending moments and the torques acting on the cutter are always changing with the variation of surrounding strata, different grouping configurations of the mechanical structures will result in various ability to rectifying deviations and bearing impacts. As a result, load calculation and mechanism modeling become two necessary components of performance analysis for a shield tunneling machine.

A shield tunneling machine can be regarded as an underground robotic manipulator [8] and most current researches about the analysis of its thrust system is mainly based on theories of parallel mechanisms with actuation redundancy. Li et al. [9] proposed a general nonlinear time-varying dynamic model and analyzed the effect of physical parameters such as gear backlash and transmission error on the mechanical performance of the thrust system with their model. Both Liu et al. [10]

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http://dx.doi.org/10.1016/j.autcon.2016.12.004
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and Deng et al. [11] presented a force transmission model based on Jacobian matrix for the redundant-actuated thrust system of the shield tunneling machine and conducted the selection for the optimum grouping strategy according to an index on the thrust force's variation. One of the most significant research findings is the force transmission model proposed by Deng et al. In [12], the force ellipse's eccentricity of the thrust system was investigated based on Lagrange Function to analyze the force transmission characteristics with non-equidistant arrangements of cylinders. In [13] a spatial deformation ellipse model was presented to study the variable stiffness-deformation characteristics of a shield tunneling machine, aiming to find better layout configurations for its thrust system. In [14] the layout arrangement of the jacks was optimized based on the force transmission spatial ellipse aiming to realize even application of forces on rear segments.

Load calculation can generally be realized in two ways: experimental measurement and theoretical model. Due to the complexity of tunneling experiment, theoretical analysis on thrust load is more frequently used in the field of shield tunneling research. The dynamic load model presented by Sugimoto et al. [15,16] is accepted as the first comprehensive theoretical model, where several key construction parameters such as the excavated area and the cutter head's rotation were included in load calculation. Afterwards, improved theoretical models were gradually developed and becoming prevalent. Wang et al. [17] analyzed the roughness of the results from an empirical load equation and proposed a novel composite model whose accuracy could be improved by experimental data and further theoretical analysis. On the basis of empirical load models, Ates et al. [18] investigated the statistical correlations between TBM diameter and excavation capacity with a database of TBMs with various design parameters and thus presented a TBM selection approach that was tested in Turkish tunneling projects. Load analysis based on contact stress presented by Zhang et al. in [19] was a sufficiently accurate model for load prediction and an improved model was established to calculate the excavating load for soil-rock interbedded strata. In [20], theoretical analysis of tangential load and normal load was conducted to be compared with in-situ data, validating the correctness of the original model.

According to the above investigation, our research will concentrate on three aspects of improvements on the existing findings of force transmission model and excavating load calculation. Firstly, all the force transmission models were deduced in terms of static force balance without consideration of dynamic characteristics in tunneling projects. Secondly, constraints which restricted a shield tunneling machine into 3-DOF (degree of freedom) motion were not analyzed. Lastly, the bending moments acting on the cutter head in composite strata were seldom analyzed in existing load models.

In the current paper, the force transmission model between the driving forces in the hydro-cylinders and the external forces is studied, and the necessary cutting loads and surrounding resistant forces are calculated with regard to the characteristic parameters of composite strata. According to the mean square error of the driving forces in hydro-cylinders, an index on force distribution uniformity is then proposed to evaluate the grouping strategy of a thrust system. Finally, in searching for optimum performances, the grouping strategy of a shield tunneling machine in curvilinear tunneling projects under impacts is investigated with numerical simulation, which can serve as helpful instructions for the grouping mode design of future thrust systems.

2. Dynamics model of thrust system

2.1. Analysis on the mechanism of thrust system

The motions of a shield tunneling machine are restricted in a quasi-cylinder by constraint forces from surrounding strata:

1) The vertical motion of the shield tunneling machine perpendicular to the excavating axis is restricted by the upper and lower stratum;
2) The lateral motion of the shield tunneling machine perpendicular to the excavating axis is restricted by the left and right stratum;
3) The rotating motion of the shield tunneling machine along its own symmetry axis is restricted by the circumferential friction between the surrounding strata and the shield.

Therefore, a working shield tunneling machine contains only 3 independent motions: propelling, yawing and pitching. Due to the fact that the constraint forces are enough to prevent relative movements, the restrictions from the surrounding strata can be converted into a massless passive PU chain (Fig. 1), where P denotes a prismatic joint and U denotes a universal joint.

Because shield tunneling is a dynamic process, the position and direction of the constraint chain will change with the movement of the cutter head. In our model, the junction point which connects the cutter head and the prismatic joint is coincident with the center of the universal joint and thus the displacement of the prismatic joint is tiny. Additionally, the position of the universal joint is related to the direction of a composite rotation and the direction of the axis of the prismatic joint is always consistent with the normal of the cutter head.

Moreover, the thrust device of a shield tunneling machine consists of n parallel-arranged hydro-cylinders, which are jointed to the cutter head and the segments with spherical hinges. As a result, the thrust system, composed of the cutter head, the segments and the cylinders, is possessed with the essential characteristics of a redundantly actuated n-S$\underline{P}$S parallel mechanism with 6-DOF spatial motion, where S denotes a spherical hinge and $\underline{P}$ an actuated prismatic joint [2]. Thus, with consideration of the equivalent constraint chain, the thrust system can be regarded as a redundantly actuated n-S$\underline{P}$S/PU parallel mechanism, whose schematic diagram is shown in Fig. 1.

2.2. Kinematic analysis of thrust system

Within the thrust system, the segments are directly mounted to the finished tunnel and thus act as the fixed platform, while the cutter head acts as the moving platform. Fig. 2 shows a schematic diagram of the thrust system at a random position and posture. An inertial coordinate system O_b-$x_b y_b z_b$ is established at the center of the fixed platform and a reference coordinate system O_m-$x_m y_m z_m$ is established at the center of the moving platform. S$\underline{P}$S kinematic chains are branches without any constraint and therefore the motion of the moving platform is completely restricted by the passive PU chain, which means that the moving platform can only translate along z axis with a variable l and rotate around x and y axis respectively with variables α and β. According

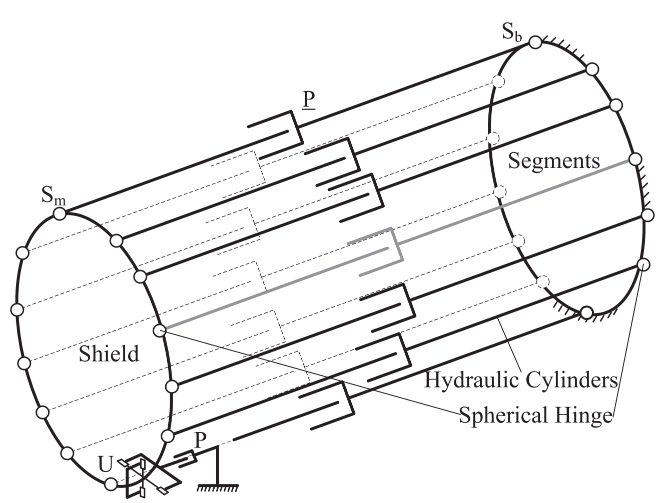

Fig. 1. A schematic diagram of a shield tunneling machine's thrust system.

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