Automation in Construction 96 (2018) 141–147

Contents lists available at ScienceDirect

Automation in Construction

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

Thrust force allocation method for shield tunneling machines under complex load conditions

Kai Guo[a,b,*], Yapeng Xu[a], Jianfeng Li[a]

[a] Key Laboratory of High Efficiency and Clean Mechanical Manufacture of Ministry of Education, Department of Mechanical Engineering, National Demonstration Center for Experimental Mechanical Engineering Education, Shandong University, Jinan 250061, China
[b] State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Keywords:
Shield tunneling machine
Complex thrust load conditions
Thrust system
Force allocation

ABSTRACT

Thrust system is one of the most important subsystems in the shield tunneling machines. Multiple hydraulic cylinders in the thrust system provide the required thrust force and help to overcome the large load torque in the excavating process, which is a typical over-actuated mechanical system. Therefore, load distribution among thrust cylinders will be uneven in the face of large load torques, which is the primary cause of cracks in lining segments. To handle this problem, most of the existing works focus on thrust system layout optimization for a predetermined geological condition. Consequently, the optimization results cannot adapt to varying thrust load conditions. We aim to provide a more flexible solution for this problem by using a reconfiguration strategy based on a force-on-off principle, which can dynamically determine whether a cylinder in the thrust system outputs force or not. Illustrative examples show that the reconfigurable thrust system ensures more even force distribution among thrust cylinders under varying thrust load conditions compared with the traditional thrust system and does not require extra hardware cost, which verifies the flexibility and effectiveness of the proposed method.

1. Introduction

Shield tunneling machines (STMs) have been widely used in modern tunnel constructions, which makes a safe and economical solution for creating underground space and opens the possibility of building tunnels that were not feasible before [1-3]. In general, the shield tunneling machine includes three major subsystems, i.e., the cutter head driving system, the lining system and the hydraulic thrust system. The cutter head is driven by a group of hydraulic/electric motors, and its two important roles is to excavate the front soils and support the tunnel face. The tunnel lining is built using the lining system located at the end of the machine to support the free face. A multi-degree-of-freedom manipulator places the prefabricated concrete segments on predetermined positions, and thus a segment ring is formed as the tunnel lining. The thrust system consists of a jacking frame and several groups of hydraulic cylinders [4]. In the excavating process, all the hydraulic cylinders push their cylinder rods directly against the lining segments that are located at the end of the machine, and therefore, large thrust force can be generated to drive the machine ahead, which is a typical over-actuated mechanical system [5]. The cylinder output force can be accurately regulated through dedicated hydraulic circuits and closed-loop control methods, which has been extensively studied in Ref. [6].

The thrust force is an important construction parameter for STM; as a result, a lot of work has been done to construct an accurate thrust force model in the past few decades [7-9]. For a given STM, the forward resistance force depends on geological conditions, the earth pressure, the friction force between the shield surface and the surrounding earth [9,10], etc. Consequently, in non-homogeneous geological conditions, load torques in the horizon and the vertical orientations arise along with the resistance force as pointed in Ref. [11]. Excessive load torque will result in severe uneven force distribution among thrust cylinders, and this offset load is one of the main causes for lining segment cracks [12]. A layout optimization method for thrust cylinders was proposed in Ref. [13] to solve this problem, in which a performance index named as force ellipse eccentricity was chosen as the cost function. The optimization process is based on the assumption that each thrust cylinder output force can be independently controlled and the cylinder arrangement is optimized under a predetermined geological condition. However, in real engineering applications, all the hydraulic cylinders in the thrust system are divided into several fixed (usually four or five)

* Corresponding author at: Key Laboratory of High Efficiency and Clean Mechanical Manufacture of Ministry of Education, Department of Mechanical Engineering, National Demonstration Center for Experimental Mechanical Engineering Education, Shandong University, Jinan 250061, China.
E-mail address: kaiguo@sdu.edu.cn (K. Guo).

https://doi.org/10.1016/j.autcon.2018.08.016
Received 27 June 2018; Received in revised form 12 August 2018; Accepted 28 August 2018
0926-5805/

groups to facilitate controller design and reduce system cost [14], which brings particular difficulties to the optimization and the implementation. What's worse, thrust load conditions may vary significantly in the excavating process [15], and therefore the optimization result for a predetermined load condition is likely to fail under other load conditions. A similar method can be found in Ref. [16], and it is suitable for tunnel lines with little change in load force conditions due to its limited adaptability.

The objective of this paper is to achieve uniform thrust force allocation for STM under complex thrust load conditions. Based on a force-on-off principle, a thrust system reconfiguration method is proposed, which results in a more uniform force distribution among thrust cylinders under complex geological conditions. Besides, the proposed strategy is based on the traditional fixed-group cylinder arrangement, and thus additional cost is avoided. The main contributions of this paper are as follows: (1) A thrust force allocation method under complex thrust load conditions is proposed, which is a flexible reconfiguration solution for the thrust system. It provides a simple but effective solution for the thrust force allocation problem regarding force allocation evenness under complex thrust load conditions. (2) The superior performance of the proposed method is verified through illustrative case studies.

The rest of the paper is organized as follows. Force transmission characteristics of traditional fixed-configuration thrust system that is widely used in engineering applications are analyzed in Section 2. In Section 3, the proposed force allocation method is given. Illustrative case studies are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. Force allocation characteristics of traditional fixed-configuration thrust system

Fig. 1 shows a simplified diagram of a STM. The rotating cutter excavates the soil while the thrust system pushes the shield ahead. All the hydraulic cylinders in the thrust system press their cylinder rods directly against the lining segments that are located at the end of the machine. Due to the large load force and torque in the excavating process, many hydraulic cylinders are used in engineering applications, which is a typical over-actuated mechanical system. For example, a STM with a diameter of 6.4 m has more than 20 hydraulic cylinders [17]. To facilitate controller design and reduce system cost, the cylinders are divided into several fixed (usually four or five) groups in a traditional fixed-configuration thrust system (FTS). Without loss of generality, a typical four-group thrust system configuration with 22 cylinders is considered in this paper, as shown in Fig. 2. All the cylinders are uniformly distributed and sequentially numbered along the circumference, and they are divided into four groups (up, right, down and left) which are named as groups 1, 2, 3 and 4, respectively. Besides,

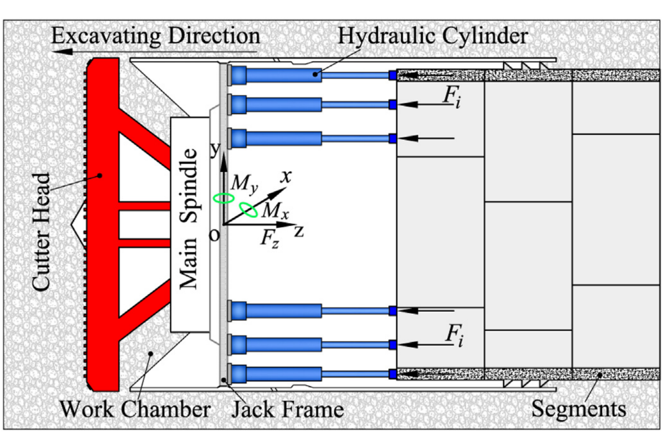

Fig. 1. Simplified mechanical model of the shield tunneling machine.

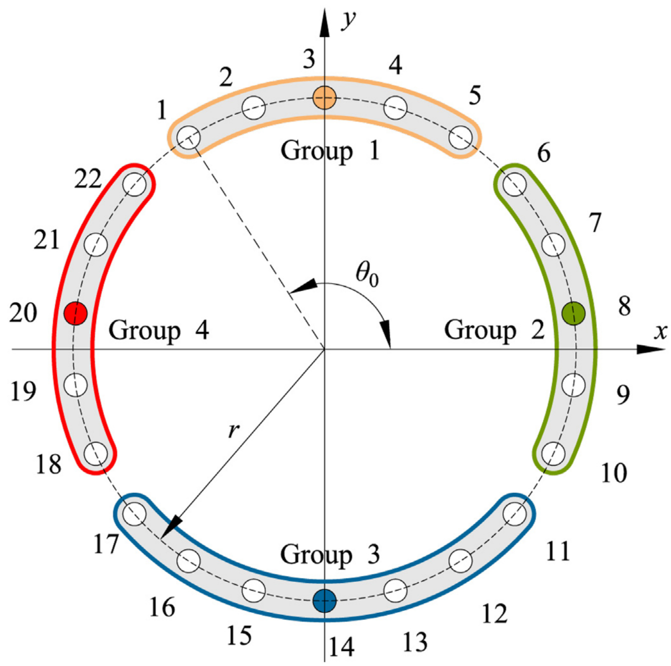

Fig. 2. Layout of the fixed-group thrust system.

one cylinder in each group is selected to measure displacement, and it is represented as an inner filled circle as shown in Fig. 2. A corresponding hydraulic circuit controls each group of cylinders, and therefore, the output force of cylinders in one group is the same.

For facilitating presentation, a Cartesian coordinate system is established (see Fig. 1). The coordinate origin locates at the cylinder distribution circle center, the z-axis is parallel with the centerline of the hydraulic cylinder and is opposite to the direction of advance, the y-axis is perpendicular to z-axis and is pointing upward, and the x-axis is determined by the right-hand rule. In Fig. 1, F_z is the resistance force in the z direction, M_x, M_y are the load torques in the x direction and the y direction, respectively, F_i is the thrust force of the cylinder in the ith group, N is the number of cylinders.

Force transmission characteristics of the thrust system can be given [12]

$$\begin{aligned} &\sum_{k=1}^{4} n_k F_k - F_z = 0 \\ &\sum_{k=1}^{4} a_k F_k - \frac{M_x}{r} = 0 \\ &\sum_{k=1}^{4} b_k F_k + \frac{M_y}{r} = 0 \end{aligned} \tag{1}$$

with

$$\begin{aligned} a_1 &= \sum_{i=1}^{n_1} \sin\left[\theta_0 - \frac{2\pi}{N}(i-1)\right] \\ a_2 &= \sum_{i=n_1+1}^{n_1+n_2} \sin\left[\theta_0 - \frac{2\pi}{N}(i-1)\right] \\ a_3 &= \sum_{i=n_1+n_2+1}^{n_1+n_2+n_3} \sin\left[\theta_0 - \frac{2\pi}{N}(i-1)\right] \\ a_4 &= \sum_{i=n_1+n_2+n_3+1}^{N} \sin\left[\theta_0 - \frac{2\pi}{N}(i-1)\right] \end{aligned} \tag{2}$$