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A new methodology for joint stiffness identification of heavy duty industrial robots with the counterbalancing system

Kun Yang[a,b], Wenyu Yang[b,*], Guangdong Cheng[b], Bingrong Lu[c]

[a] School of Material Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] State Key Laboratory of Digital Manufacturing equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[c] Huaheng Weld Co., Ltd., Kunshan 215347, China

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ABSTRACT

This paper deals with the joint stiffness modeling and identification of the heavy duty industrial robot with the counterbalancing system (CBS), which is important for the workspace optimization and deflection compensation in the robotic manufacturing. Shortcomings of the traditional method for the joint stiffness modeling and corresponding identification are analyzed in this paper. Motivated by the advantage and limitations of the traditional approach, a new identification methodology based on the servo motor current and corresponding position deflection is proposed to obtain the accurate joint stiffness. To validate the effectiveness of the proposed method for the joint stiffness modeling and identification, an identification and validation experiment is carried out using the HH-150 heavy duty industrial robot. The results show that the proposed methodology is able to identify the joint stiffness of the heavy duty industrial robot with the CBS, and the proposed new methodology outperforms in terms of accuracy, convenience and efficiency for the joint stiffness identification.

1. Introduction

Owing to the low investment and high production flexibility, recent studies have demonstrated that heavy duty industry robots are gradually becoming more competitive than the CNC machine in the manufacturing industry, such as grinding [1], boring [2], machining [3,4] and the friction stir welding (FSW) [5]. Because of high forces generated in these applications, the insufficient stiffness of robots becomes the main obstacle for high-accuracy robotic manufacturing applications [4,6]. Especially for the machining and FSW process, the process load would make the joint deform, and the deflection is produced at the end of the manufacturing tool, degrading the quality of the final product [7]. One possible way to solve this problem is to optimize the workspace or compensate the deflection based on the robot stiffness [6,8]. To implement this approach, an accurate stiffness modeling of heavy duty industrial robot as well as the corresponding stiffness identification plays an important role in the robotic manufacturing process [9], which is the main focus of this paper.

The robot stiffness describes the manipulator resistance to the deformation caused by the external force/torque applied to the end-effector (EE). Usually, the characteristic of the robot stiffness is numerically defined as a Cartesian stiffness matrix, which represents a linear relation between the translational/rotational displacement and force/torque in the EE. Similarly, the joint stiffness denotes the relation between the force/torque and corresponding deflections in the joints. In general, methods for the robot stiffness modeling are roughly divided into three groups: the Finite Elements Analysis (FEA), the Matrix Structure Analysis (MSA), and the Virtual joint method (VJM) [10]. The basic principle of the FEM method is to decompose the physical model of the structure on a number of finite elements and to introduce compliant relations between adjacent nods described by relevant stiffness matrices. As it considers the true shape and dimensions of the robot, the FEM method seems to be the most accurate one for the stiffness modeling [11]. Nevertheless, due to the high computational efforts and numerous accumulative round-off errors, this method is usually applied at the design stage [12]. To overcome the high computational effort, the MSA method is proposed to obtain the stiffness matrix by using beams, arcs and cables instead of complex links [13]. However, this simplification inevitably reduces the modeling accuracy. Meanwhile, the factor of assembling is also the key contribution of the stiffness matrix, and it cannot be accurately modeled by these two methods. The VJM method deals with the robot stiffness based on the extension of the traditional rigid-body model by adding virtue joints (localized springs), where links are regarded as rigid while the joints are assumed to be

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[*] Corresponding author.
E-mail address: mewyang@hust.edu.cn (W. Yang).

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compliant [9,14,15]. This method provides reasonable trade-off between the model accuracy and identified complexity, and it will be used for the stiffness modeling in this paper.

Salisbbury [16] and Gosselin [17] are the first researchers to introduce the VJM method for the robot stiffness analysis. In their studies, the main compliance of the robot is assumed to be concentrated in the joints, and the mapping of stiffness matrices between the Cartesian and joint spaces is put forward. Later, Chen and Kao [18] reported that the conventional formulation derived by Salisbbury was not valid and a new conservative congruence transformation was used as a generalized relationship between the joint stiffness matrix $\mathbf{K}_{\boldsymbol{\theta}}$ and Cartesian stiffness matrix $\mathbf{K}_{\mathbf{X}}$. Based on this study, an enhanced stiffness modeling, identification and characterization for robot manipulators is proposed by Alici [19]. For the enhanced model, a complementary stiffness matrix $\mathbf{K}_{\mathrm{c}}$ is added in the conventional stiffness model by considering the external load and robot configuration. Subsequently, Dumas [20,21] proposed a robust procedure for the joint stiffness identification of the industrial robot based on the analysis of the complementary matrix $\mathbf{K}_{\mathrm{c}}$. Recently, Klimchik [9] proposed a sophisticated stiffness model based on the VJM method, which takes into account flexibilities of all mechanical elements.

To enhance the stiffness and payload capability of the heavy duty industrial robot, manufacturers tend to increase the link cross-section that inevitably leads to the augmentation of the robot mass. As a result, the second joint always bears the worst load during heavy duty applications. Therefore, the CBS is usually applied to minimize the torque in the second joint, which considerably complicates the stiffness modeling and identification. However, the problem of joint stiffness modeling for the robot with CBS has been rarely reported in current researches. One of the relevant works is devoted to regarding the CBS as an equivalent virtual spring [22,23]. In this study, the equivalent stiffness of the CBS is identified simultaneously with the joint stiffness. Nevertheless, the classical method for the joint stiffness identification is performed by the measurement of applied loads and corresponding deflection of the EE. In this way, it may be impossible to accurately obtain the spring stiffness, as the influence of the CBS on the second joint is almost eliminated by the comparison of these two robot states, before and after loading (namely, the influence of the CBS before loading is almost the same as that after loading). Besides, for the heavy duty industrial robot, such as Kuka KR-500MT and HH-150 (self-developed by Huaheng Weld Co., Ltd), the CBS is composed of the hydro-pneumatic system, and it is not reasonable to simplify the CBS to the virtual spring. To improve the modeling and identification accuracy of the CBS, a new methodology reflecting the clear physical meanings of the CBS is proposed in this paper.

Apart from the stiffness modeling and identification of the CBS, the traditional method for the joint stiffness identification has several shortcomings, which is assumed that the applied loads measured by the force sensor is the sole factor for the joint deformation. Actually, the practical force contributing to the deflection after loading is not the same as the measurement of the force sensor. Meanwhile, positions of three more reference points are required to obtain the orientation deflection, causing the placement error of the measurement system under each joint configuration. And the detailed problem for the joint stiffness modeling and identification of the heavy duty industrial robot is stated in Section 3.

Motivated by the advantage and limitations of the current research, a new and more accurate methodology is proposed for the joint stiffness identification of the heavy duty industrial robot with the CBS. The main attention is paid to the new theoretical stiffness model and corresponding identification method. The content of this paper is organized as follows. In Section 2, the kinematic model of the heavy duty industrial robot with the CBS and the joint stiffness model are presented. Section 3 describes the study motivation, which is based on problems for the joint stiffness identification. A new methodology for the joint stiffness identification is proposed in Section 4. Section 5 describes the identification experiment and corresponding results of the HH-150 robot based on the proposed method. In Section 6, the experiment is carried out to validate the identified joint stiffness. Finally, Section 7 summarizes the main contribution of this paper.

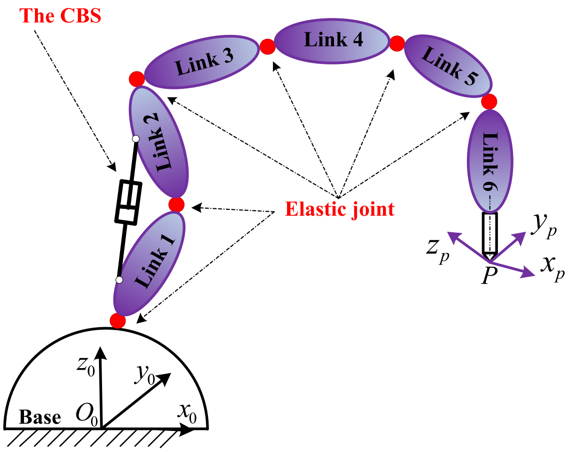

Fig. 1. The VJM model of the HH-150 robot.

2. Kinematics and joint stiffness modeling

2.1. Forward kinematics of the HH-150 robot

As illustrated in Fig. 1 and Fig. 2, the HH-150 robot can be represented as a sequence of rigid links separated by elastic joints based on the VJM model. Meanwhile, the CBS is attached to the first and second links, which generates the balancing torque for the second joint. When the robot is under heavy duty applications, the real joint position θ_i has two components: the command joint position and the deformed position caused by the force/torque [24].

$$\theta_i = q_i + \Delta\theta_i \tag{1}$$

Where q_i denotes the command joint position, and $\Delta\theta_i$ represents the deformation of the ith joint.

The CBS is a passive mechanism, whose kinematics is determined by the second joint variable θ_2. Thus, kinematics of the heavy duty industrial robot is only relative to the joint position vector $\boldsymbol{\theta}$, and all issues related to kinematics are identical to those of the conventional rigid robot [24]. In this case, the transformation between each two adjacent links is defined as

$$\mathbf{T_i} = Rot(x, \alpha_{i-1})Trans(a_{i-1}, 0, 0)Rot(z, \theta_i)Trans(0, 0, d_i) \tag{2}$$

Where $\mathbf{T_i}$ is the homogenous matrix representing the transformation of the ith link frame to the $i-1$ th link frame, and the details of the

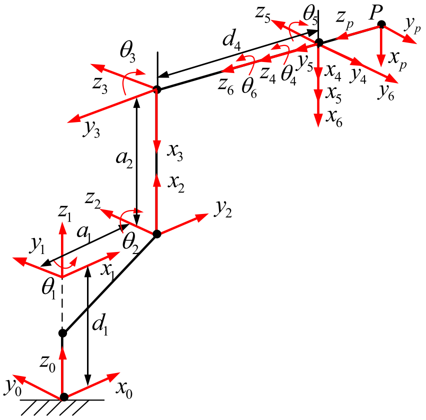

Fig. 2. D-H parameters of HH-150 robot.