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Control-orientated dynamic modeling of forging manipulators with multi-closed kinematic chains

Wen-Hua Ding [a,b], Hua Deng [a,b,*], Qun-Ming Li [a,b], Yi-Min Xia [a,b]

[a] The State Key Laboratory of High-performance and Complex Manufacturing, Changsha 410083, China
[b] School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China

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ABSTRACT

The dynamic model, particularly with reference to controller design, is an important issue in mechanical control and design. However, this model is often difficult to achieve in complex multi-closed-loop mechanisms, such as parallel mechanisms or forging manipulators. A new approach on the dynamic modeling of a multi closed-chain mechanism in a forging manipulator, which applies screw theory and the reduced system model, is proposed in this paper. The proposed method not only allows a straightforward calculation of actuator forces but also obtains the dynamic equation of the multi-closed-loop mechanism easily. The structure of dynamic model obtained is similar to that of standard Lagrangian formulations, which can extend vast control strategies developed for serial robots to complex multi-closed-loop mechanisms. A complex multi-closed-loop mechanism on a forging manipulator is decomposed into several serial mechanisms or simpler subsystems. The Lagrangian equations associated with each subsystem are directly derived from the local generalized coordinates of the sub-mechanisms. Jacobian matrices are used to interpret the differential equations of the sub-mechanisms into the generalized coordinate or the actuated pairs according to the D'Alembert principle. Hessian matrices are also applied to form a standard Lagrangian formulation. The screw theory is introduced to overcome the difficulties of solving transformed Jacobian matrices, thereby simplifying the calculation of the matrices. Computation difficulties of transformation matrices may decrease considerably by choosing suitable generalized coordinates instead of direct actuator variables. The full dynamics of the complex multi-closed-loop mechanism in a forging manipulator is presented. Simulations and experiments illustrate the reliability of the proposed method and the correctness of the dynamic model of the forging manipulator.

1. Introduction

The forging manipulator, whose main task is to hold and manipulate the work piece in heavy forging, is indispensable for the improvement of manufacturing ability, forging quality, safety, efficiency, and so on. With the development of forging automation, numerous researchers have intensely studied the crucial role that forging manipulators play in the forging industry [1–7]. A forging manipulator includes a gripper carrier that is connected to a truck frame through one or more connected closed-loop kinematic chains to improve payload capacity. The gripper carrier can be moved horizontally, vertically, and rotationally in a plane. These directions are three main motions of a forging manipulator during forging. Therefore, the main motion mechanism in a forging manipulator is a complicated 3-DOF multi-closed-loop planar mechanism (i.e., this mechanism is referred to as "parallel robots" in robotics literature). The parallel manipulator has grown popular and has received increasing attention recently because of its advantageous features such as low weight/load ratio, high rigidity, and high accuracy [8,9]. The manipulators are characterized by complex kinematic relations, leading to complex dynamic equations because dynamics is a natural extension of kinematics. Therefore, most investigations focus on the kinematic issues of complex mechanisms, whereas few researches refer to dynamics modeling and analysis [10]. Unlike open-chain mechanisms, a well-established motion equation exists in dynamics and robotics literature. In addition, many control results have been developed. Deriving an effective dynamic model for controller design is necessary to ensure that serial counterparts are available for multi-closed-loop mechanisms [11,12]. The solutions used for the dynamic modeling of complex manipulators have two basic approaches, namely Recursive Newton–Euler formulation and Lagrangian formulation. The Recursive-Euler formulation has poor

* Corresponding author at: School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China. Tel.: +86 731 8883 6769.
E-mail address: hdeng@csu.edu.cn (H. Deng).

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computational efficiency since all internal reaction forces between bodies are considered, even if they do not apply to the control law design of the manipulators [13]. Lagrangian method, which is an energetic approach, may be classified into two groups: direct Lagrangian and Lagrange–D'Alembert formulation on the reduced system. Direct lagrangian is usually applied to open-chain robots or some particular multi-closed-loop mechanisms. In addition, many serial robot dynamic models are derived based on direct Lagrangian equations and many control methods have been developed for the dynamic model in the field of robotics as well. Lagrange–D'Alembert formulation on the reduced system is used mostly for the dynamic modeling of the parallel manipulator or complex multi-closed-loop mechanisms, but the equations are of sheer complexity and not easy to obtain because explicit relations between the different coordinates (actuated and passive or non-actuated) have to be calculated [14,15]. To apply the existing research achievements of the serial robotic field, deriving multi-closed chain-manipulator dynamic equations with structures similar to open-chain manipulator equations is necessary [16–18]. In light of aforementioned reasons, most studies focus on kinematic and optimization issues on the basis of the kinematic model of forging manipulators [1,2,19], whereas relatively few researches refer to the dynamics of multi-DOF and multi-loop mechanisms. Although several dynamic models on forging manipulator have been developed, these models aim to achieve an optimal design and to analyze the complex mechanism instead of implementing and optimizing the model-based controller [3,4,20]. This research bottleneck obstructs the performance improvement of forging manipulators and the development of forging automation.

Wittenburg introduced the notion of a *reduced system* [21], which is a tree system obtained from a multi-closed-loop mechanism by cutting certain joints. The dynamics of the tree system can be easily obtained through the existing dynamics and robotics literature. The D'Alembert principle is applied to formulate a transformation between generalized actuating forces and to obtain the final dynamic equation of the closed-loop mechanism with a structure similar to that of standard Lagrangian formulations [16–18,22]. The generalized actuating force transformation plays a decisive role in combining the explicit dynamic model of the closed-chain mechanism using the dynamic equations from the tree system. However, the transformation matrices between generalized actuating forces or dependent generalized coordinates and independent generalized coordinates are usually difficult to obtain because the calculation of a large number of Jacobian and Hessian matrices among independent and dependent generalized coordinates is necessary [14]. Given that multi-closed-loop mechanisms are characterized by complex kinematics relations, calculating the Jacobian and Hessian matrices of the complex mechanical system is complex because of the geometric constraints caused by the multi-closed loop topology [4]. Therefore, on the basis of the *reduced system dynamic method*, obtaining the dynamic model with a standard Lagrangian form for the complex multi-closed-loop mechanism is difficult.

Many researchers started resorting to advanced mathematical tools such as Lie group theory and screw theory to solve the kinematic and dynamic problems of complicated parallel manipulators [13,23–25]. In particular, screw theory has made enormous progress in the kinematics and dynamics of open or closed chains [13,25–33]. More than two decades ago, screw theory has been proved an efficient tool for solving the first-order analysis of closed chains, that is, kinematic Jacobian. As shown in [26,30], although screw theory can be applied to the acceleration analysis of closed chains, the expressions appear to be complicated, thereby restricting the application of screw theory in obtaining a dynamic model of multi-closed-loop mechanism in analytical standard form because dynamics is a natural extension of kinematics. Currently, the complicated mechanism dynamic model represented with a screw form is usually used for mechanism analysis or numerical simulation [13,25,31]. To the best of our knowledge, obtaining the analytical dynamic equation of complex mechanisms with a structure similar to that of standard Lagrangian formulations is still unexplored through screw theory.

In this paper, the dynamic equations of a complex multi-closed-loop mechanism in a forging manipulator are developed through a novel method that combines screw theory and the *reduced system dynamic method*. Screw theory is introduced to cope with transformation matrices for *reduced system* on the basis of the first-order analysis advantage on the kinematics of open serial and closed chains, which is extending results previously obtained by authors [13,30,32]. A complex multi-closed-loop mechanism in a forging manipulator is decomposed into several serial mechanisms or simpler subsystems on basis of the *reduced system dynamic method*. The whole system dynamics is approached by an harmonious combination of the subsystems' equations and the transformation matrices according to the D'Alembert principle. A 3-DOF multi-closed-loop mechanism in a heavy-duty forging manipulator is taken as a case study to show the effectiveness of the presented method. Dynamics is validated by ADAMS simulation and using a small-scale forging manipulator's experiment, respectively.

2. Problem formulation

2.1. Dynamics of rigid bodies

A multi-loop complex mechanism consists of many rigid bodies and joints. Expected motions are carried out if the rigid bodies and joints are arranged in an organized interconnection, i.e., only when rigid bodies or components perform coordinated motions, the mechanism can complete a given task. At the same time, a multi-loop mechanism of holonomic constraints can be decomposed into several serial manipulators by cutting certain joints, i.e., a *reduced system* [21].

In the absence of friction and other disturbances, if a complex mechanism has N DOF, then the standard dynamic model of a complex mechanism not in contact with the external environment can be described by the following set of ordinary differential equations using Lagrangian dynamics [34]:

$$\boldsymbol{D}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{\tau} \tag{1}$$

where[1] $\boldsymbol{q}\in\Re^N$ is the vector of generalized coordinates; $\boldsymbol{D}(\boldsymbol{q})\in\Re^{N\times N}$ denotes the inertia matrix; $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\in\Re^{N\times N}$ represents the Coriolis and centrifugal terms; $\boldsymbol{g}(\boldsymbol{q})\in\Re^N$ represents the gravitational terms; $\boldsymbol{\tau}\in\Re^N$ is the vector of generalized force.

Eq. (1) also can be presented as follows:

$$\boldsymbol{D}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\dot{\boldsymbol{q}}^T\boldsymbol{H}_C(\boldsymbol{q})\dot{\boldsymbol{q}}+\boldsymbol{g}(\boldsymbol{q})=\boldsymbol{\tau} \tag{2}$$

where $\boldsymbol{H}_C(\boldsymbol{q})\in\Re^{N\times N\times N}$ denotes the Hessian Force matrix for the mechanism. This matrix is a three-dimensional tensor with N layers, in which each layer is a $N\times N$ matrix.

Similarly, the dynamics of the serial mechanisms from the *reduced system* also can be represented by (2). If the ith serial mechanism is an n'-DOF mechanism, then the dynamic equations can be written as follows:

$$\boldsymbol{D}_i(\boldsymbol{q}_i)\ddot{\boldsymbol{q}}_i+\dot{\boldsymbol{q}}_i^T\boldsymbol{H}_{C_i}(\boldsymbol{q}_i)\dot{\boldsymbol{q}}_i+\boldsymbol{g}_i(\boldsymbol{q}_i)=\boldsymbol{u}_i \tag{3}$$

where $\boldsymbol{q}_i\in\Re^{n'}$ is the vector of generalized coordinates of the ith subsystem or module; $\boldsymbol{D}_i(\boldsymbol{q}_i)\in\Re^{n'\times n'}$ is the $n'\times n'$ inertia matrix of

[1] In the following discussion, $\Re$ denotes the set of real numbers; $\Re^N$ is the usual N-dimensional vector space over $\Re$; $\Re^{N\times M}$ and $\Re^{N\times M\times K}$ denotes the set of all $N\times M$ and $N\times M\times K$ matrices with real elements, respectively.