Stiffness Modeling and Optimization Analysis of a Novel 6-DOF Collaborative Parallel Manipulator*

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Abstract. This article presents a novel 6-DOF cooperative parallel manipulator assembled by two independent 3-DOF parallel manipulators that can complete tasks through relative motion. It provides broader workspace, higher stiffness and better controllability for high precision machining demands compared to traditional parallel kinematics manipulator. The architectures of the two 3-DOF parallel manipulators are firstly stated, followed by inverse kinematics analysis and stiffness analysis through establishing global Jacobian matrix. Finally the cooperative parallel manipulator's static stiffness and modal analysis are conducted. First order of natural frequency optimization is established so that optimal radius of drive rod can be achieved. Comparing the results before and after optimization, it can be seen that performances are obviously improved.

Keywords: cooperative parallel manipulator, kinematics, stiffness, parametric optimization.

1 Introduction

Over the past two decades, many efforts have been put on cooperative serial robot (CSR) and hybrid cooperative manipulator (HCM). CSR, inheriting the feature of serial mechanism, adds 1~3 DOFs on the work piece to generate cooperative machining between tool and work piece, which broaden the workspace and can undertake the machining of more complex surface. Attractive results have been achieved, such as Chang, K. S.'s analyses on cooperative manipulation [1], Liu, Y. H.'s cooperative control research [2]. HCM, combined of series robot and parallel manipulator, provides not only broader workspace and large mass/stiffness ratio but also low accumulative error, which gains an advantageous place in multi-DOF complex surface machining [3]. Waldron, K. J. designed a hybrid series/parallel 6-DOF manipulator and researched into the dualities of motion screw axes and wrenches with Ball [4, 5]. Shahinpoor, M. and Sklar, M. came up with a novel

* This work was financially supported by the National Natural Science Foundation of China (No. 51175105), the Shenzhen Key Lab Fund of Advanced Manufacturing Technology (No. CXB201203090033A) and the Shenzhen Research Fund (No. SGLH20131010144128266, JCYJ20140417172417129).

X. Zhang et al. (Eds.): ICIRA 2014, Part II, LNAI 8918, pp. 60–71, 2014.

parallel-serial robot and researched into its kinematics and dynamics [6, 7]. Yet the presence of serial mechanism in both CSR and HCM makes it unsuitable in high precision machining, which leads to the idea of cooperative parallel manipulator (CMP).

CMP that means that two parallel manipulators cooperate to accomplish assigned tasks, which obviously provides broader workspace, larger mass/stiffness ratio and lower accumulative errors, is proposed [8]. All these advantages reduce the cost and improve the practicability. Joint efforts have been made into realizing this wonderful idea [9, 10]. However, most work has been focused on structure analysis, control strategy and the scope of application [11, 12], very few of which systematically researched on its performances. Therefore, current researches on CPM machine tool are very limited, which hinders its application in manufacture.

This paper is organized as follows: in Section 2, the architecture of CPM is described and in Section 3 the inverse kinematic which is based on a closed-loop vector method is presented. In Section 4, the stiffness of parallel manipulator is derived. In Section 5, mathematic model is established between the first order natural frequency and parameters of drive rods, which is used for optimizing the size of the CPM. The conclusion is drawn in the last section.

2 Description of the CPM

A novel 6-DOF CPM machine tool that can cooperate to complete given tasks, is designed as shown in Fig. 1. These two manipulators, designed according to screw theory [13], are placed up and down. The upper manipulator, a 3-PSC/PU parallel manipulator, is the tool system, which can rotate around *x*, *y* axis and stretch out/draw back along *z* axis. The lower manipulator, a 3-PU*R parallel manipulator, is able of translation along *x*, *y*, *z* axis, which is named work piece system.

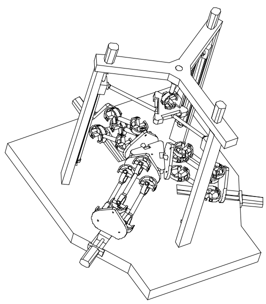

Fig. 1. 3-D schematic representation of a general CPM

Tool system, as shown in Fig. 2(a), consist a moving platform, a fixed base and three limbs of identical kinematic structure which are 120° symmetric distribution. Each limb connects the fixed base to the moving platform by a P joint, a S joint and a C joint in sequence, where the P joint is actuated by a linear actuator assembled on the fixed base. A central passive limb connects the fixed base to the moving platform by a