Fusion Engineering and Design 86 (2011) 1838–1842

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Static stiffness modeling of a novel hybrid redundant robot machine

Ming Li*, Huapeng Wu, Heikki Handroos

Laboratory of Intelligent Machines, Lappeenranta University of Technology, Finland

A R T I C L E I N F O

Article history:
Available online 12 February 2011

Keywords:
ITER
Parallel robot
Stiffness
Matrix structural analysis

A B S T R A C T

This paper presents a modeling method to study the stiffness of a hybrid serial–parallel robot IWR (Intersector Welding Robot) for the assembly of ITER vacuum vessel. The stiffness matrix of the basic element in the robot is evaluated using matrix structural analysis (MSA); the stiffness of the parallel mechanism is investigated by taking account of the deformations of both hydraulic limbs and joints; the stiffness of the whole integrated robot is evaluated by employing the virtual joint method and the principle of virtual work. The obtained stiffness model of the hybrid robot is analytical and the deformation results of the robot workspace under certain external load are presented.

1. Introduction

The ITER vacuum vessel sectors are made of 60 mm-thick stainless steel which are joined together by the high efficiency structural and leak tight welds. The stringent tolerances of assembly, ±5 mm, are expected, while high dynamic machining force and high accuracy are required for cutting, weld repair and weld preparation. To satisfy the machining capacity of mobility and flexibility in a limited space inside the ITER vacuum vessel, a hybrid parallel robot (IWR in Fig. 1) has been developed, which has ten degrees of freedom (DOF); six degrees of freedom are contributed by a Stewart parallel mechanism and the rest by the serial mechanism [1].

Generally, in the high dynamic force application of assembly of ITER, the deflection of robot will be getting big and the accuracy will be getting poor. To compensate or to limit the deflection, the stiffness of robot should be studied. This paper focuses on the stiffness modeling of the robot. The developed model can be used for compensating the deflection of robot to reach high accuracy, and it can also be used for trajectory planning to find higher stiffness poses of the motion.

In this paper, a stiffness modeling method is developed for the proposed hybrid robot IWR. Based on this method, the matrix structural analysis (MSA) [2] approach is employed to calculate the stiffness of the basic element in the Stewart of robot, e.g., the universal joint (U-joint) and the bearing house; the virtual joint method (VJM) [3,4] combined with the principle of virtual work is also applied to evaluate the stiffness of the combined structure, e.g., the base of the Stewart; the stiffness of the Stewart is evaluated by taking account of the deformations of six base joints and the hydraulic limb deformations; the stiffness of the whole integrated robot is obtained by considering the Stewart and the serial basement as connected in serial.

The remainder of this paper is organized as follows: Section 2 introduces a general methodology of the MSA; Section 3 describes the modeling of the typical Stewart structure; Section 4 gives a finial stiffness model by integrating the parallel mechanism and the serial mechanism; Section 5 presents the numerical results of stiffness; and Section 6 summarizes the main contributions of this work.

2. Description of matrix structural analysis

The schematic representation of the kinematic chain of the IWR is presented in Fig. 2.

The coordinate $X_0^gY_0^gZ_0^g$ is defined as the global frame, and all local coordinates are related to the global frame: $X_1^gY_1^gZ_1^g$ moves along the gear track and $X_2^gY_2^gZ_2^g$ along the ball screw; $X_3^gY_3^gZ_3^g$ rotates around the Z_2^g axis; $X_4^gY_4^gZ_4^g$ is the basement coordinate of the Stewart and rotates around the X_3^g axis; $X_5^gY_5^gZ_5^g$ is fixed in the centre of the end-effector as the tool frame.

The analytical stiffness model of the basic element evaluated in this paper is based on MSA. In order to illustrate the application of the MSA on the multi-beam structure, the stiffness modeling of bearing house and U-joint in the base side of Stewart platform in the robot is taken into account (Fig. 3).

For simplification, the bearing house, U-joint and the base are described by the frame structure in Fig. 4.

For applying the MSA method we firstly define the elements of structure and their nodes. Each element of structure is defined by a number enclosed with a circle, and its two nodes by two numbers. A local coordinate is given for each element.

* Corresponding author at: CEID-Center, Lappeenranta University of Technology, Faculty of Technology, Skinnarilankatu 34, 53850 Lappeenranta, Finland.
Tel.: +358 465941828.
E-mail address: hackingming@gmail.com (M. Li).

0920-3796/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2011.01.018

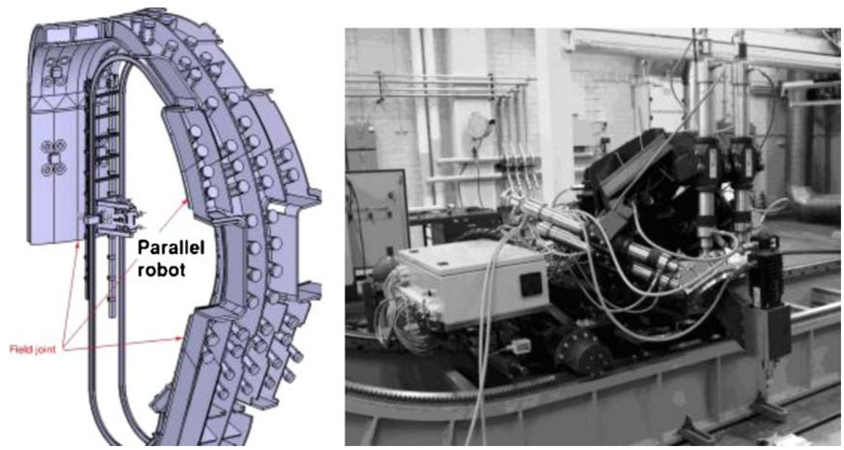

Fig. 1. 10DOF hybrid robot for the assembly of ITER: (i) vacuum vessel and (ii) robot used for the assembly of vacuum vessel.

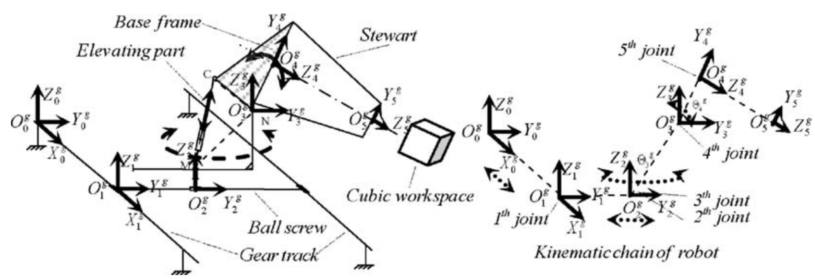

Fig. 2. Schematic diagram of hybrid robot.

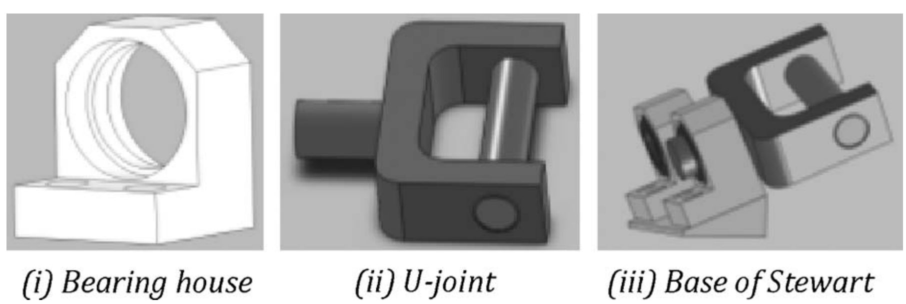

Fig. 3. Base of Stewart: (i) bearing house, (ii) U-joint, and (iii) base of Stewart.

In Fig. 4(iii), O_0^bA is the base frame of Stewart platform, $O_1^uO_6^u$ the frame of U-joint, and ABO_1^u the frame of bearing house including the U-joint shaft. Firstly, we decompose the bearing house and the U-joint into separate beams in Fig. 4(i) and (ii), and then we obtain the stiffness matrix for each beam by applying the MSA. Finally all these stiffness matrices are assembled according to the node connectivity by the superposition principle and expressed in the local coordinate system. Herein, the stiffness modeling of U-joint is:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} = \begin{bmatrix} K_{11}^{2}+K_{11}^{3} & K_{12}^{2} & K_{13}^{3} & O & O & O \\ K_{21}^{2} & K_{22}^{2}+K_{22}^{4} & O & K_{24}^{4} & O & O \\ K_{31}^{3} & O & K_{33}^{3}+K_{33}^{5} & O & K_{35}^{5} & O \\ O & K_{42}^{2} & O & K_{44}^{4}+K_{44}^{6} & O & K_{46}^{6} \\ O & O & K_{53}^{5} & O & K_{55}^{5}+K_{55}^{7} & K_{56}^{7} \\ O & O & O & K_{64}^{6} & K_{65}^{7} & K_{66}^{6}+K_{66}^{7} \end{bmatrix} \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \Delta_5 \\ \Delta_6 \end{bmatrix} \quad (1)$$

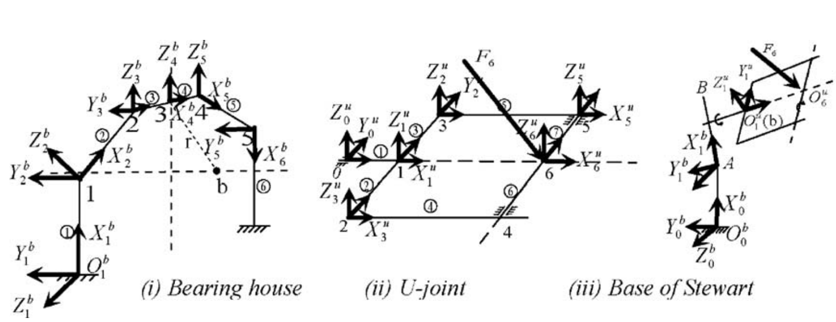

Fig. 4. Schematic diagram of frame structure: (i) bearing house, (ii) U-joint, and (iii) base of Stewart.