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Compliance Induced Deformation Prediction of Parallel Kinematic Machine

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Abstract. Parallel Kinematic Machines (PKM) demonstrate the capability of adapting to modern, flexible manufacturing systems due to their higher flexibility and improved motion dynamics. Compliance of a machine tool has a significant impact on the performance, which directly contributes to the quality of the machined workpiece. Compliance deformations result in inaccuracies in the geometry of the machined part. Therefore, prediction of compliance deformation helps to determine the geometrical quality. To fill in the knowledge gap, this paper presents a compliance-induced geometrical error prediction method based on a semi-analytical stiffness model.

Keywords. PKM, Stiffness, Geometrical quality

1. Introduction

Parallel Kinematic Machines (PKMs), or parallel robots, are a type of robotic system commonly used in modern, flexible manufacturing applications. A PKM system consists of a closed-loop kinematic chain with multiple links connected in parallel. PKMs are flexible as serial robots, superior in dynamic performances as traditional CNCs and demonstrate a high stiffness-to-mass ratio [1]. Due to their improved motion dynamics and positioning accuracy, they are widely used in machining, drilling and milling operations, such as aircraft structures where large workpieces need to be processed with higher accuracy. Incorporating these features and performances, a number of commercialised PKMs can be found in the industry, such as Tricept [2], Exechon [3], and A3 sprint head [4].

Compliance of a machine tool is one of the significant properties which determines the performance of the machine tool. Compliance-induced deformations directly affect the geometrical quality of the machined workpiece. Therefore, the prediction of compliance deformation helps to determine the geometrical quality of the machined workpiece. Due to the closed loop structure and configuration dependency, compliance modelling of PKM is rather challenging. In the literature, there are three main approaches can be identified for PKM compliance modelling, namely, (I) numerical approach with FEA [5], [6], (II) analytical approach based on structural matrix [7], [8], and (III) semi-

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analytical method based on virtual works principle [9], [10]. After employing one of the aforementioned methods to predict the compliance of the machine tool, a compliance deformation analysis can be conducted to obtain the compliance induced deformations of the machine tool. Zhang et al. [11] introduced a compliance deformation analysis technique for non-redundant parallel manipulators based on principle axes decomposition of compliance matrices. Nakagawa et al. [12] presented a method for compensating gravity-induced errors in Stewart platform based PKM by utilising the elastic deformations of struts, caused by gravity. Similarly, Eastwood et al. [13] proposed a gravitational deformation compensation method for hybrid PKM. However, there is a scarcity of studies in the literature on compliance deformation analysis of PKMs. Therefor, this paper aims to bridge the research gap by introducing a method for predicting compliance induced deformations in PKMs based on a semi-analytical stiffness model that considers the effect of gravity. First, this paper describes stiffness modelling of PKMs considering the effect of gravity, followed by the generation and analysis of stiffness of the workspace. Finally, the paper presents the prediction method of compliance deformations within the workspace.

2. Stiffness modelling of PKM considering the effect of gravity.

The semi-analytical stiffness prediction model developed by López-Custodio et al. [10], [14] for Exechon X-mini robot was used as the base of this study. The Exechon X-mini robot (Figure 01) is a hybrid robot with two main substructures i.e., 3-DoF parallel module and a 2-DoF serial module. The parallel module consists of a moving platform connected to the fixed base platform using three legs. There are two types of leg structures used in the robot. The upper two legs identified as leg 1 and 3 are UPR serial chains, while the other leg identified as leg 2 is a SPR serial chain. Here U, P, R and S stand for universal, prismatic, revolute and spherical joints respectively. To develop the overall stiffness model for the entire robot structure, the stiffness of the parallel module and the serial module are considered as two individual elements. The stiffness of each module was developed separately and combined them considering as two serially connected sub-systems.

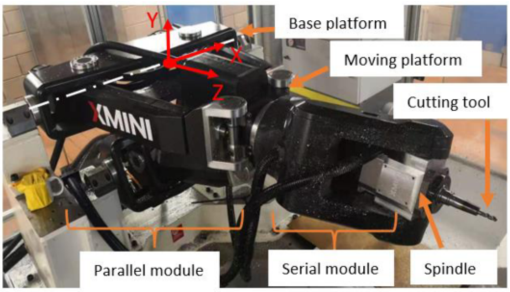

Figure 1. Sub-structures of Exechon X-Mini manipulator.

In the previous model, the effect of gravity was not considered in the model parameter identification. Therefore, the proposed study was conducted to re-calibrate the existing stiffness model to predict the stiffness of the machine tool including the effect of gravity.

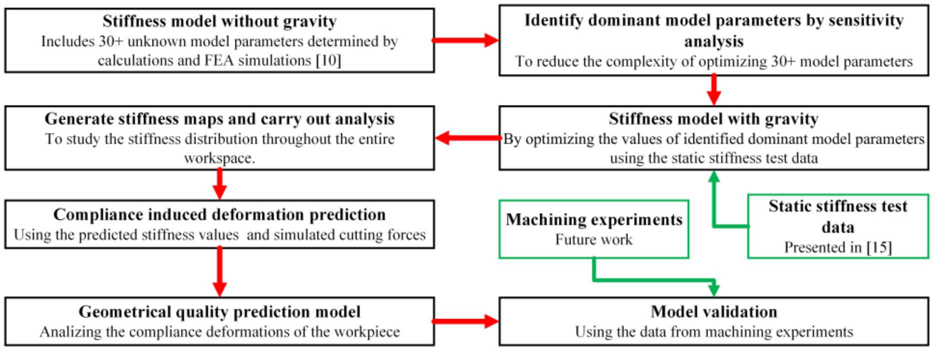

Figure 2. Flow diagram of the proposed stiffness modelling method.

Figure 2 represents the overall procedure followed to obtain the stiffness of the machine tool, including the effect of gravity. Parameters of the existing stiffness model [10] were re-calibrated to predict the stiffness including gravity utilising an experimental data based parameter optimisation. This model consists of approximately thirty-five model parameters and the stiffness of the machine tool K is described as a function of those parameters as shown in Eqn. (1).

$$K = f(CG1x, CG1y, CG1z, CG2x, CG2y, CG2z, CG3x, CG3y, CG3z, cMp, \dots) \quad (1)$$

Optimising a higher number of model parameters is not feasible due to limited experimental data, limited processing power and extended optimisation time. To overcome this issue, two methods were considered. The first method was to run the optimisation in multiple stages selecting 5-7 variables to optimise each time. This method is time-consuming and requires more experimental data. Therefore, a sensitivity analysis was conducted to identify the most sensitive model parameters towards the stiffness of the machine tool. From the sensitivity analysis, six model parameters were identified as the most sensitive parameters. Then, experimental data were used to optimise the identified model parameters. To gather experimental data for the optimisation, a unique experiment procedure was developed to separate the effect of gravity on stiffness from the machine tool structure. Static stiffness of the X-mini machine tool in the X, Y and Z directions were measured experimentally under externally applied force on the tool tip in each direction respectively. The complete experimental procedure and gravity effect analysis of the robot based on experimental data was previously presented in [15]. After that, optimised model parameters shown in Table 01 were used in the stiffness model, and the stiffness of the machine tool related to each coordinate of the workspace was obtained. Using these stiffness values, stiffness maps were generated to represent the variation of stiffness throughout the workspace.

Table 1. Identified sensitive model parameters and corresponding optimised values.

Parameter	$CG1x$	$CG2z$	$CG3y$	$CLgimy$	cLy	cMp
Value (mm/N)	1.0000e-07	8.9063e-05	4.6875e-06	4.6875e-06	2.1511e-08	6.2000e-05

Upon analysing the stiffness maps, initially, a compliance deformation analysis was conducted specifically for the Z direction. The deflections of the tooltip in the Z direction for a given coordinate is denoted as δ_z. The stiffness in the Z directions denoted as K_z was acquired from the stiffness prediction model. The cutting forces acting on the Z direction denoted as F_z was obtained for a specific combination of cutting tool and process parameters through the utilization of a cutting force simulation software [16]. Consequently, by applying the Hooke's law in the Z direction, the compliance deformation δ_z of the selected coordinate is derived as shown in Eqn. (2).

$$\delta_z = \frac{F_z}{K_z} \tag{2}$$

3. Stiffness map generation and stiffness analysis.

After optimizing the stiffness model with new experimental data as described in section 2, initially, the model was used to predict the stiffness of the machine tool on the test point coordinates. The calculated stiffness using experimental results were compared with the predicted stiffness without using the optimised parameters in X, Y and Z directions. The model was able to predict the stiffness with a maximum error of 10.62%, 28.69% and 26.77% in X, Y and Z directions respectively. Then, the model was used to predict the stiffness of the machine tool in entire workspace assuming that a 100N cutting force is acting on each direction.

Figure 3 represents the stiffness variation maps, developed based on the predicted stiffness values. Figure 3. (A). illustrates the stiffness variation of the machine tool in X direction. It shows lower value at the edges of the workspace, and it gradually increase the value towards the centre of the workspace. Also, the stiffness of the X direction is symmetrical about X=0 and Y=0 axes and the highest stiffness is recorded at Z=1300, followed by Z=1400, while the minimum stiffness is observed at Z=1500. According to Figure 3. (B). the stiffness of the machine tool in Y direction also shows lower values at the edges of the workspace and increase the value towards the centre of the workspace. It is symmetrical about X=0 axis but asymmetrical about Y=0 axis. Similar to the stiffness in X direction, the stiffness in Z direction also shows lower values at the edges of the workspace and increase its value towards the centre of the workspace and the highest stiffness is recorded at Z=1300, followed by Z=1400 and Z=1500. Figure 04 illustrates the stiffness variation maps in the Z direction.

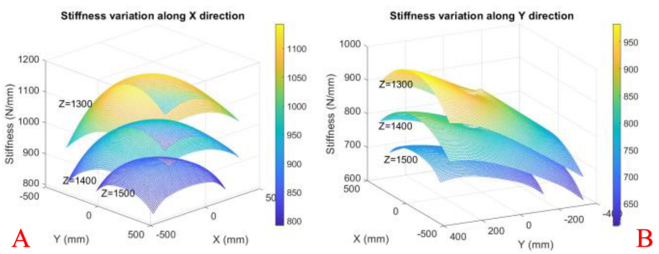

Figure 3. Stiffness variation of the machine tool for Z=1300, 1400 and 1500, (A): X direction, (B): Y direction

Compared to the stiffness in X and Y directions, Z direction has the highest stiffness. It is also symmetrical about X=0 axis but asymmetrical about Y=0 axis. In contrast to the stiffness variation of X and Y directions, the stiffness in the Z direction increases with the Z values. The highest stiffness is observed at Z=1500, followed by Z=1400 and the minimum stiffness is recorded at Z=1300. Upon analysing the graphs, the area under

X ranges from -200 to +200, Y ranges from +100 to +350 and Z ranges from +1300 to +1500 are identified as the workspace with higher stiffness.

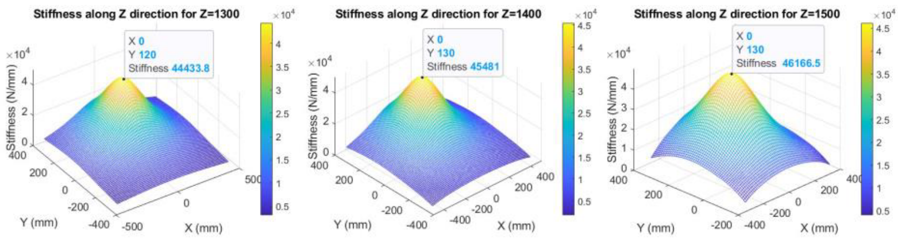

Figure 4. Stiffness variation of Z direction for Z=1300, 1400 and 1500

4. Compliance induced deformation prediction.

After analysing the stiffness maps in Section 3, initially, the deformation analysis was conducted in the Z (axial) direction of the machine tool, specifically for the identified area with higher stiffness. The deflection of the tooltip in Z direction was calculated applying the Eqn. (01) using the predicted stiffness and simulated axial cutting force of 110.4 N. Figure 05 represent the deflection variation of the machine tool in Z direction for Z=1400, 1500 and 1600. It is visible from the graph, that the deflection of the tooltip lies between 2-18 µm range for all presented Z values.

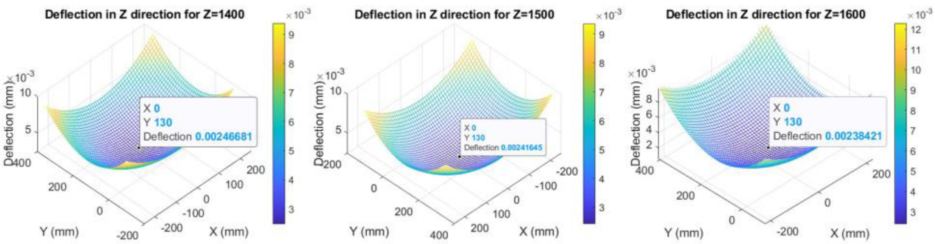

Figure 5. Deflection variation of Z direction for Z=1400, 1500 and 1600

5. Conclusion

In this study an experimental data-based parameter optimization method is introduced to predict the stiffness of a Exechon X-mini machine tool using a semi-analytical stiffness prediction model considering the effect of gravity on machine tool structure. The model was able to predict the stiffness in X, Y and Z directions with a maximum error of 10.62%, 28.69% and 26.77% respectively. The workspace area covered by X (-200 to +200), Y (+100 to +350) and Z (+1300 to +1500) is identified as the area with highest stiffness. Then the predicted stiffness values were used to calculate the compliance induced deformation of the tool tip in Z direction. The predicted deformation lies in between 2-18 µm range for the selected workspace, tool and process parameter configuration. This identified area can be used to place the workpiece for a given machining task to reduce the errors due to compliance deformations. With further validation and testing, this model can be used to predict the geometrical quality of the machined workspace. Experiments will be conducted to validate the proposed model as the next step.

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