Kinematic and Dynamic Analysis of the 3-PRS Parallel Mechanism Based on Virtual Prototype

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Abstract: Aiming at the complicated problem of kinematic and dynamic analysis, the method based on the virtual prototype technology is proposed to study the 3-PRS parallel mechanism. The 3D modeling software is discussed to establish the virtual prototype. The virtual prototype modeling procedure is proposed and presented, and then the virtual prototype of the 3-PRS parallel mechanism is established. Finally four examples are given to verify the feasibility and effectiveness of the prototype. The established prototype lays a foundation for further study of the 3-PRS parallel mechanism.

Keywords: Parallel mechanism, Virtual prototype, Kinematic analysis, Dynamic analysis, 3D modeling

I. INTRODUCTION

The parallel mechanism, called parallel robot sometimes, has many advantages of high precision, strength and stiffness and good carrying capacity, and has gained plenty of application in all kinds of fields, such as machining tools, driving simulators, recreation equipments and medical apparatus and instruments[1-7]. Not all the parallel mechanisms possess 6 degrees of freedom (DOFs), and the deficient DOF mechanism has Broad application and presents prominent performance in many fields, among which the 3-PRS parallel mechanism with two parasitic rotational motions and one parasitic translational motion is typical in the deficient DOF parallel mechanism. The characteristic of the 3-PRS mechanism is very complicated because it includes working space, kinematics, dynamics and so on. The theoretical analysis procedure refers to the nonlinear equation system and trigonometric functions, and the analysis procedure and solution is always complicated, confusing, tedious and non intuitive. The physical experiment has the real performance and the mechanism can present its real characteristics. But the characteristic is the result of many influencing factors, so it is always very difficult in finding the causal link between the influencing factor and the extrinsic phenomenon. In addition, the physical is always expensive and time-consuming. The virtual prototype technology can reduce development expenses, shorten development cycle and improve design performance. Therefore a virtual prototype for the 3-PRS parallel mechanism is established to analyze its kinematic and dynamic characteristic.

II. ARCHITECTURE OF THE 3-PRS PARALLEL MECHANISM

The 3-PRS parallel mechanism is composed of a moving platform, three limbs, three vertical rails and a fixed platform (base)[8-12], as shown in Figure 1. Three vertical rails vertically link to the fixed platform (base) B₁, B₂, B₃. Moreover, B₁, B₂ and B₃ form an equilateral triangle that lies on a circle with the radius R. The axis of each revolute pair cᵢ for i = 1, 2 and 3 is perpendicular to the corresponding prismatic pair. Each limb Lᵢ for i = 1, 2 and 3 connects the corresponding rail by a prismatic pair Cᵢ. The moving platform and three limbs are connected by three spherical pairs P₁, P₂ and P₃.

Three spherical pairs form an equilateral triangle that lies on a circle with the radius r. The cutter is placed at the center of the moving platform. The feeds of the three prismatic pairs are given as Hᵢ for i = 1, 2 and 3. The angle θᵢ for i = 1, 2 and 3 is defined from the vertical rail to its corresponding limb Lᵢ. As shown in Figure 1, a fixed Cartesian reference coordinate system OXYZ is located at the center point O of B₁, B₂, B₃. The X-axis and the Y-axis are in the base plane B₁, B₂, B₃, the X-axis points in the direction of O B₁, and the Z-axis is normal to the base plane and points upward. The 3-PRS parallel mechanism possesses 3 DOFs that are a rotational motion about the Z-axis, a rotational motion about the Y-axis, and a translational motion along the Z-axis.
III. ESTABLISHMENT OF THE VIRTUAL PROTOTYPE

There are a great number of excellent three-dimensional design /CAD/simulation packages that can be used to establish the virtual prototype, such as SolidWorks developed by Dassault Systemes S.A, UG(Unigraphics NX) developed by Siemens PLM Software, CATIA (Computer Aided Three-dimensional Interactive Application) developed by Dassault Systemes, Pro/E(Pro/Engineer) developed by PTC(Parametric Technology Corporation) and ADAMS(Automatic Dynamic Analysis of Mechanical Systems) developed by Mechanical Dynamics Inc. And every of these packages has its advantages and disadvantages. The kinematic and dynamic characteristic of a mechanical mechanism can be fully exploited by combination with other computation software, such as MATLAB (MATrix & LABoratory) developed by MathWorks, Maple developed by Waterloo Maple Software and Mathematica developed by Wolfram Research.

The virtual prototype is established in a two-stage procedure shown in Figure 2 and some schematic assembly icons are excerpted from CATIA. The first stage includes modeling the each part of the 3-PRS mechanism. It should be noticed that maybe several parts are modeled as a whole one or a certain some part is replaced in other way in order to simplify the task. The parts are assembled in the second stage.

If a 2-DOF X-Y table is introduced and fixed bellow the fixed platform(base), a 5-DOF series-parallel robot is built and the corresponding virtual prototype is shown in Figure 3.
IV. RESULTS

Example 1: The characteristic highly depends on the mechanism parameter. The limb length is 820mm, the radius $R$ and $r$ are 350mm and 150mm respectively and the cutter length is 150mm. The moving trajectory is expressed as

$$
\begin{align*}
    x &= 15\cos(2\pi t) \\
    y &= 15\sin(2\pi t) \\
    z &= 0 
\end{align*}
$$

The feed $H_i$ of the three prismatic pairs can be computed and the Point Control algorithm is used. The load force is along the cutter axis. The Coulomb friction model is utilized with the static friction coefficient and dynamic friction coefficient set. The simulation results are shown in Figure 4.

Example 2: The limb length is 1107mm, the radius $R$ and $r$ are 350mm and 200mm respectively and the cutter length is 280mm. The slider moving law is set as

$$
\begin{align*}
    H_1 &= 3107 - (100t + 10r^2) \\
    H_2 &= 3107 - (100t + 9r^2) \\
    H_3 &= 3107 - (100t + 9r^2) \\
    0 \leq t \leq 10
\end{align*}
$$

If $H_3$ is replaced by $3107 - 200r$ and $3107 - (90t + r^2 + t^3)$ respectively, the cutter trajectories are shown in Figure 5.
Example 3: The test structure parameters for Example 2 is used again but now with the three slider velocities expressed as

\[
\begin{align*}
    v_1 &= 50 + 2t + 3t^2 + 0.16t^3 \\
    v_2 &= 50 + 25t \\
    v_3 &= 50 + 25t
\end{align*}
\]

for \(0 \leq t \leq 10\) (3)

The cutter trajectory and velocity are shown in Figure 6.

Example 4: The test structure parameters for Example 2 is used again. The first and second slider accelerations are set as \(35 \text{ mm/s}^2\), and the first accelerations is set as \(40 \text{ mm/s}^2\), \(20+6t\) and \(24t-4.8t^2\) in sequence. The cutter trajectory and velocity are shown in Figure 7.
V. CONCLUSION

The 3D modeling software is discussed to establish the virtual prototype. The virtual prototype modeling procedure is proposed and presented, and then the virtual prototype of the 3-PRS parallel mechanism is established. Finally four examples are given to verify the feasibility and effectiveness of the prototype. The established prototype lays a foundation for further study of the 3-PRS parallel mechanism, for example finite element analysis for error and structural strength.

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