The Effects of Revolute Joint Clearance on the Kinematic Behavior of the 3RPR Planar Parallel Manipulator

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1. Introduction

Mechanical joint defects might highly influence the dynamic response of the whole multibody system. Affecting the transient behavior, the joint clearance yields noise and vibration with a reduction in the component life.

The aim of this study is the kinematic and dynamic analysis, considering the clearance in the simulation of a 3-RPR planar parallel manipulator where the three prismatic joints are actuated.

The ideal and non-ideal model, without and with clearance in the revolute joints, are compared in the results to show the effect of clearance in the robot performance, such as an illustration in path tracking.

2. Planar Parallel Mechanism 3-RPR

The planarthree-DOF3-RPR mechanism has a parallel structure, including a fixed base and a moving platform, called end-effector (EE). These types of parallel manipulators are mainly used in making fast operations and accurate simulators. Three planar chains are connected to the moving platform in a triangular planar kinematic chain.

It is assumed that the center point of the end effector creates a specific path with a constant velocity in the plane regard to the kinematics chains. Using the inverse kinematic equations in the ideal case, the inputs and their derivatives can be computed. Now, given these inputs, one can solve the direct kinematic in the presence of clearance. Then, the generated trajectory of point *C* can be calculated and compared with the desired path. Moreover, the joints forces and the accelerations of the links can be computed for both cases, that is, in the presence and absence of the clearance in the joints.

In this case, the complexity of the robot's kinematic and dynamic relationships increases greatly. As a result, ADAMS Software is used here to overcome the numerical difficulties for non-ideal joints. Researchers have addressed this method to simulate and analyze parallel robots, indicating the high quality and reliability in dynamic simulation.

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The geometrical equation could be written based on the difference in the radius of the different surfaces in terms of displacements and lead to the distance between two levels g as kinematic contact condition. The situation where the contact is lost corresponds to $g>0$ with zero contact force, whereas the contact with local deformation referred to as a penetration, corresponds to $g<0$. Acritical factor, in the precise prediction of the impact force, is the type of the selected contact model.

3. ADAMS Modeling

ADAMS is the most widely used software for multibody simulation and motion analysis. ADAMS in this paper helps us understand the dynamics of a parallel mechanism involving the moving realistic non-ideal revolute joint.

Clearance modeling

In planar mechanisms, the clearance of each hinge joint adds two degrees of freedom to the system, which can include horizontal and vertical displacements of the pin center relative to the bearing center. During motion, the interaction of surfaces is based on vertical and tangential forces at the point of contact.

Contact modeling

In ADAMS, the impact model and restitution model are two models that are utilized for the surface contact definition. In this paper, IMPACT-Function-Based Contact is employed.

The normal force of the contact has involved elastic and viscous damping. The rigidityis a function of the penetration and the viscous damping is dependent on the speed of penetration.

4. Simulation

Before extracting and reviewing simulation results, the robot modeling accuracy in software should be ensured. To this end, linear accelerations of the end-effector (EE) is compared in three different ways: (1) the robot's kinematic analytic solution in the ideal state, (2) modeling without clearance joints in software, (3) robot modeling with clearance joints in software considering a very small clearance (Cl=0001 mm).

During the robot path tracking, kinematic curves in diagrams are very close together. The impact forces in the joints, as expected, create a deviation representing error signal in the diagrams, which results from a clearance in the joints. Therefore, it is possible to confirm the correctness of the software modeling and its proper functioning during this model validation.

ADAMS result

Figure 1 shows the 3-RPR manipulator that is modeled by ADAMS software, including six non-ideal revolute joints and rigid links. The simulation examines the EE center point kinematics in three different clearance sizes (0.00001mm, 0.5 mm, and 1mm).

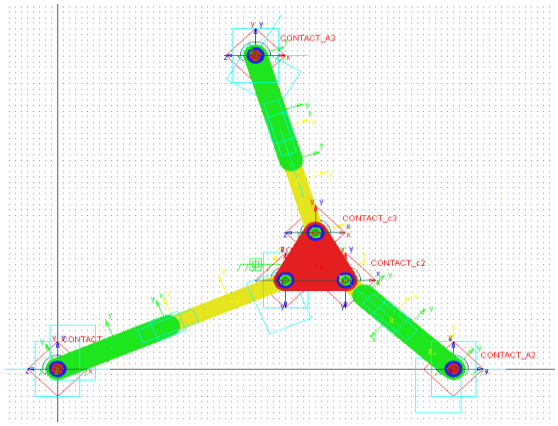

Figure 1. The 3-RPR parallel manipulator with clearance revolute joints

The dynamic behavior of the manipulator with the effects of the clearance joints is analyzed by plottingthe position, velocity, and acceleration (linear/rotational) for different clearance sizes. For instance, it is clearly shown that the magnitudes of the accelerations change sharply in the presence of joints clearances when it leads to contact.

The magnitude of clearance size obviously affects the end-effector acceleration. The manipulator experiences higher accelerations for the larger clearance sizes. In spite of kinematic analysis in this paper, one can expect higher impact forces at the joints in the kinetic analysis.

According to the diagrams which demonstrate kinematic parameters, it can be seen that by increasing the size of the joint clearance, the error rate increases significantly compared to the ideal state and the EE pose is affected. Figure 2 shows the rotational changes of the EE with the size of the joints clearance. These changes in rotational positions in oneparallel robot can easily spoil the robot's performance. Therefore, if the parallel mechanism is used to produce ahigh accuracy path, special attention should be paid to the effects of clearance in creating errors.

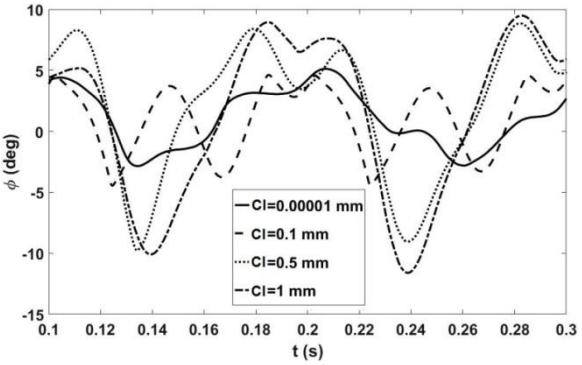

Figure 2. Rotational changes of the EE with clearance size

FFT Frequency Analysis

The discrete Fourier transform may be used to identify periodic structures in time series data. It is approved the significant effects of the clearance on the time domain dynamic response. However, due to the less focus on frequency domain analysis with clearance, Fast Fourier Transformation (FFT) is performed. Since the existence of clearance causes high-frequency vibration of the acceleration, this signal is used to analyze the frequency spectrum of the vibration characteristics. The peaks of vibration amplitude in FFT analysis results with varying clearance sizes areincreased as the clearance size increases. Moreover, increasing the clearance size will carry a lower frequency of contact. It means that with a larger clearance, the contact phase is appeared for a longer period.

4. Conclusion

In this work, a 3-RPR with a focus on the revolute joints was modeled. The parallel robot with clearance revolute joints has been modeled and simulated in the ADAMS as dynamic analysis software. The simulation results are compared for the two ideal joints, without clearance, and the real joints. It has been shown that if there is a clearance in the hinged or revolute joints, the velocity and acceleration of the end-effector (and other mechanism members) are increased relative to the ideal joint within a perfect design. Additionally, FFT analysis proves the joint clearance effect on decreasing of the motion stability.

As a result, special attention should be paid to factors such as wear and unbalance in the system dynamics that increase corrosion in the joints and thus increase clearance. On the contrary, an increase in the acceleration of the members and, consequently, the emergence of high forces during the robot's performance should be expected.