The Effects of Joint Clearance on the Dynamics of the 3-RPR Planar Parallel Manipulator

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Abstract: In reality, clearances in the joints are inevitable due to the defects arising from manufacturing process, design tolerances, and wearing after a certain working period. It leads to a chaotic behaviour including the impact loads which results in an unpredictable response in the system. Since clearance introduces an additional uncontrollable degree of freedom to the manipulator, it causes error and could not be neglected in the manipulator design. In this study, the dynamic behaviour of a planar mechanism with revolute joints, in the presence of clearances is investigated. The planar 3-RPR parallel manipulator with six revolute clearance joints is modelled in MSC.ADAMS software and the simulation results are presented. Moreover, the effects of clearance size on the dynamic characteristics of a planar mechanical system are analysed and compared. What is found out is the prediction of the dynamic error due to the joints clearance for this parallel robot.

Keywords: Dynamic effect, Joint clearance, 3RPR Planar parallel manipulator

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1 INTRODUCTION

Parallel mechanisms have attracted the attention of many researchers with growing applications in robotics, machine tools, positioning systems, measurement devices, and so on [1] – [4]. It has been proved that such a closed-loop mechanism has a great potential and advantages over the traditional opened-loop mechanism. The main advantage of parallel mechanisms is the high positioning accuracy due to their inherent rigidity [5]. High rigidity is provided in the condition without non-ideal effects such as clearance and backlash. Since the parallel mechanisms are capable of imparting a net force on an arbitrary object to produce a controlled and repeatable movement of the object receiving a complete motion, the clearance can reduce the rigidity which is achieved by the parallel structure.

In this condition, for all various degrees of freedom, a parallel mechanism's end-effector shows position and orientation errors [6]. In the conventional kinematic and dynamic analysis of robotic systems, each joint is characterized as a perfect adjustment; i.e., clearance, wear and manufacturing tolerances are not considered. However, clearances in the joints are inevitable due to tolerances and defects arising from manufacturing and design. Therefore, this issue has attracted the attention of researchers recently [7] – [12].

Earles and Wu introduced a model based on permanent contact condition [13]. In the model, clearance is replaced by a mass-less virtual link that connects the journal center to the bearing center. Using the general trend of the Hertz contact law, Lankarani and Nikravesh developed a contact force model in which a hysteresis damping function was incorporated with the intent to represent the energy dissipated during the impact [14]. Flores and Ambro'sio used contact force approach to model and simulate the performance of a slider–crank mechanism with one clearance joint [15].

Flores et al. investigated the friction between the journal and the bearing and its effects utilizing a modified coulomb's friction law [16]. Moreover, Schwab et al. compared several models of contact forces [17]. They analyzed and simulated a slider–crank mechanism with one clearance joint of rigid or flexible connecting rod, for both dry and lubricated contact conditions. Varedi et al. [18], [19] used Lankarani–Nikravesh model and proposed a method to remove the impact forces in the clearance joints by optimizing upon the mass distribution of the links. It is noteworthy that all the above studies focus on the revolute joints and mechanisms with one degree of freedom (DOF), and the reported work for the manipulators and joints with more than 1-DOF is scarce [20], [21].

Jawale and Thorat studied positional error in 2-DOF mechanism with joint clearance [22]. Altuzarra et al. performed the positioning discontinuities due to clearances in parallel manipulators [23]. They introduced a methodology for analyzing the location of discontinuities by means of dynamic and kinetostatic analysis. Li-Xin and Yong-Gang [24] investigated the joint clearance effects on the dynamic performance of a planar 2-DOF pick-and-place parallel manipulator. Moreover, Farajtabar et al. [25] investigated the problem of pick-and-place trajectory planning. To be specific, they studied the 3-RRR planar parallel manipulator with clearance in the joints. They showed that the errors in the trajectories could be compensated by appropriate changes of the inputs. To this end, they compared the resultant trajectories with those in the ideal case. Furthermore, Varedi et al. [26] have considered the effects of joints clearance on the dynamics of the planar 3-RRR parallel manipulator and optimized it for reducing these undesirable effects [27].

The main purpose of the present work is to study the dynamic behaviour of 3R$\underline{P}$R planar parallel manipulator with rigid links, in the presence of clearance in all the passive revolute joints. In the absence of joints lubrication, the journal moves freely inside the bearing boundaries until it contacts with the bearing. When a journal and a bearing are in contact mode, deformation and the contact loss between the journal and bearing takes place. It results in a contact force, normal to the plane of collision. Finally, for numerical example, the planar 3-R$\underline{P}$R parallel manipulator is modeled in MSC.ADAMS software and the simulation results are presented.

2 PLANAR 3-R$\underline{P}$R PARALLEL MANIPULATOR

Planar 3-RPR parallel manipulator, as depicted in Fig. 1, is presented in this section. We will study the effects of clearance under the assumption that point C of the end effector (EE) creates a trajectory with a constant velocity in the plane. Using the inverse kinematic (IK) equations in the ideal case (without clearance in the joints), the inputs and their derivatives can be calculated. Now, given these inputs, one can solve the direct kinematic (DK) in the presence of clearance. Then, the generated trajectory of point *C* can be calculated and compared with the desired trajectory. Moreover, the joints forces and the accelerations of the links can be computed for both cases, i.e., in the presence and absence of the clearance in the joints.

2.1. Manipulator description

The planar 3RPR parallel manipulator is shown in Fig. 1. This manipulator consists of an equilateral triangular platform which is connected to the base by three symmetric closed-loop chains, each of which consists of a revolute joint (R), then a prismatic joint (P), and again a revolute joint (R), respectively [28]. The manipulator has 3-DOF and three prismatic actuators (in joints B1, B2 and B3), move the platform in the plane. All the revolute passive joints are considered with clearance.

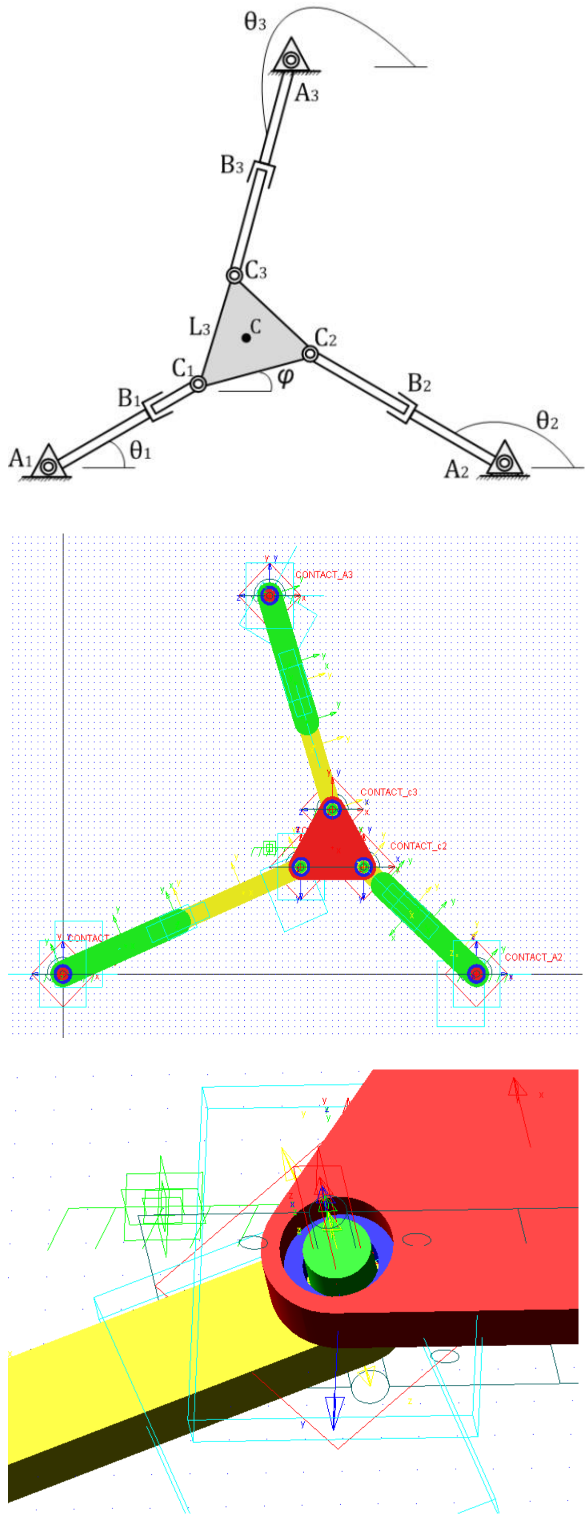


Fig. 1 The 3-RPR parallel manipulator with clearance revolute joints.

2.2. Inverse kinematics, without clearance

In this subsection, the IK of the manipulator without considering clearance in the joints is presented. IK is defined as: given the Cartesian coordinates of the EE, namely y_C, x_C and ϕ, find the actuator variables. According to Fig. 1, if the coordinates of points *Ai* and *Ci* are known, the lengths A_iC_i (i=1, 2, 3) are obtained as:

$$\left(x_{C_i}-x_{A_i}\right)^2+\left(y_{C_i}-y_{A_i}\right)^2=(\overline{A_iC_i})^2 \quad i=1,2,3 \tag{1}$$

Where the coordinates of the points Ci are:

$$x_{C_i}=x_C+(\overline{CC_i})\cos\left(\varphi+\frac{7\pi}{6}+\frac{4\pi}{6}(i-1)\right), \qquad i=1,2,3$$
$$y_{C_i}=y_C+(\overline{CC_i})\sin\left(\varphi+\frac{7\pi}{6}+\frac{4\pi}{6}(i-1)\right), \qquad i=1,2,3 \tag{2}$$

Moreover, the length of CCi is equal to L3/√3. By using the Eq. (1), one can find the inverse kinematics solution of planar 3-RPR parallel manipulator.

3 MODELING OF THE 3-RPR IN MSC.ADAMS

The software package used to develop, simulate, and analyze the dynamic models is ADAMS by MSC Software. It has a 3D environment for modelling mechanical problems and it uses its own solver to formulate and solve problems. Because of high capability of ADAMS/view software, it is used to simulate the parallel robot [29] – [31].

Fig. 1 shows the 3-RPR manipulator that is modelled in the ADAMS software, with six revolute joints and geometric data of Table 1, we built the model under ADAMS, where all links of the robot are rigid and clearance value between journal and bearing radiuses is 0.5 mm.

Table 1 Parameters of planar 3-RPR manipulator

Moving platform	Side length (C_iC_{i+1})	100 mm
	Mass	0.2 kg
Links	Density	2270 kg/m^3
	Young's modulus	73 GPa
	Poisson's ratio	0.3
Cylinders	Motion course amplitude (A_iB_i)	200 mm
Fixed platform	Side length (A_iA_{i+1})	660 mm

A model is developed by defining all parts of a system including masses and inertial properties, defining forces acting on or between these parts, and constraining the motions of the parts to each other (or totally). ADAMS develops the equations of motion of the system from the model and then solves the equations numerically in the time frame. The output of the program is the solution of the equations, from which any force acting through the system or motion of any part in the system can be obtained.

3.1. Modeling of clearance

In the revolute joints, the clearance is modeled by the introduction of two additional degrees of freedom. x and y are the horizontal and the vertical displacements of the journal center relative to the bearing center. The bearing radius is 10 mm while the journal radius is equal to 9.5 mm.

The kinematic contact condition for a revolute joint with radial clearance e and relative displacements, x and y, is given by [28]:

$$g = e - \sqrt{x^2 + y^2} \tag{3}$$

The situation where the contact is lost corresponds to g > 0 (Fig. 2), whereas the contact with local deformation, referred to as a penetration, corresponds to g < 0. A critical factor, in the precise prediction of the impact force, is the type of the selected contact model [32].

Contact between objects is an important aspect in multibody dynamics. It is a discontinuous, non-linear phenomenon and therefore requires iterative calculations. Adams, a MSC Software performs these calculations and can provide accurate results. The accuracy depends on user program knowledge and the algorithms and the selected variables.

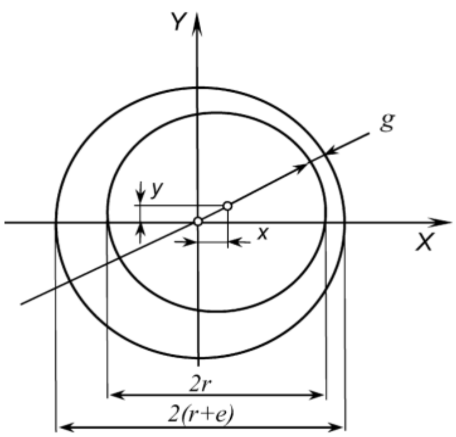


Fig. 2 Planar revolute joint with clearance [32].

3.2. Modeling of the contact

For the modeling of the contact under ADAMS, we have used the contact method based on the impact function: IMPACT-Function-Based Contact (Fig. 3). In this method, ADAMS/Solver computes the contact force from the IMPACT function available in the ADAMS function library. This impact function is activated when g ≤ 0 [32].

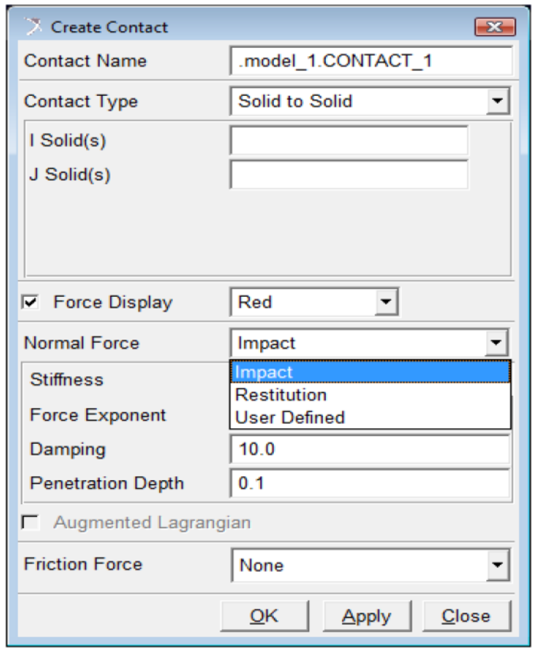


Fig. 3 IMPACT-Function in MSC.ADAMS.

The normal force of the contact has two components: rigidity and viscous damping. The component of rigidity is a function of the penetration δ = -g and the viscous damping is dependent on the speed of penetration. In this model, the normal force of contact is given by the following relation [28].

$$\begin{cases} F_N = K\delta^n + STEP(\delta, 0, 0, d_{\max}, C_{\max})\dot{\delta}, & \delta > 0 \\ 0, & \delta \leqslant 0 \end{cases} \tag{4}$$

Where K is the stiffness coefficient, which depends on the material and the radii of the solids in contact with the following expression [32]:

$$K = \frac{4}{3\pi(h_i + h_j)}\sqrt{\frac{R_i R_j}{R_i + R_j}}$$
$$h_k = \frac{1 - v_k^2}{\pi E_k}, \qquad k = i, j \tag{5}$$

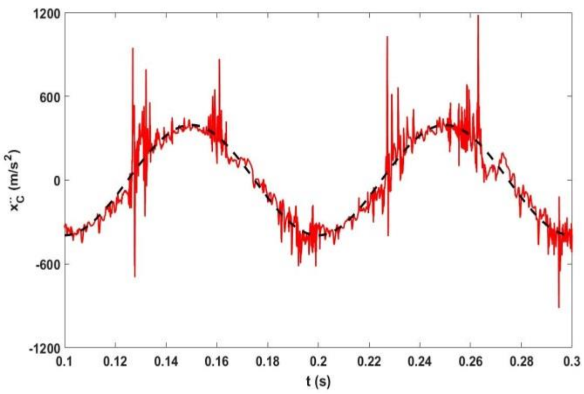
Ri, *vi*, and *Ei* represent respectively the radii, the Poisson's ratio and the modulus of elasticity for element *i*. The exponent of the force deformation characteristic, *n*, is set to 1.5 [32]. Into ADAMS, the instantaneous damping coefficient set to a cubic step function of the penetration [32]:

$$STEP(\delta, 0, 0, d_{max}, C_{max})$$
$$= \begin{cases} 0, & \delta \le 0 \\ C_{max}\left(\frac{\delta}{d_{max}}\right)^2\left(3 - 2\frac{\delta}{d_{max}}\right) & 0 < \delta < d_{max} \\ C_{max} & \delta \ge d_{max} \end{cases} \tag{6}$$

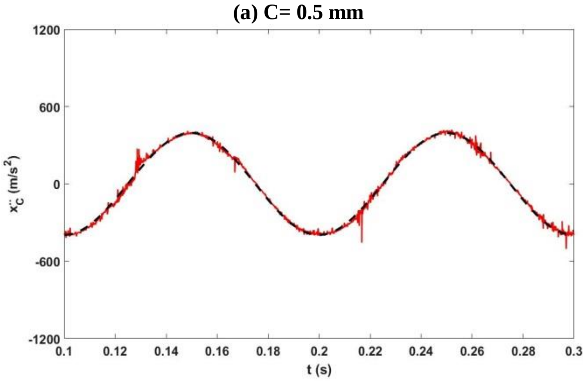
Where d_{max} is a positive real value specifying the boundary penetration to apply the maximum damping coefficient C_{max}.

4 SIMULATIONS AND RESULTS

Now, the dynamic behavior of the manipulator and effects of the clearance joints are analyzed by plotting the dynamic parameters (accelerations and forces). The linear accelerations of the end-effector (EE) in *x* and *y* directions for different clearance sizes are depicted in Figs. 4 and 5 respectively. It is clearly shown that the magnitudes of the accelerations change sharply in the presence of joints clearances. Moreover, the angular accelerations of the EE for different clearance sizes are shown in Fig. 6.



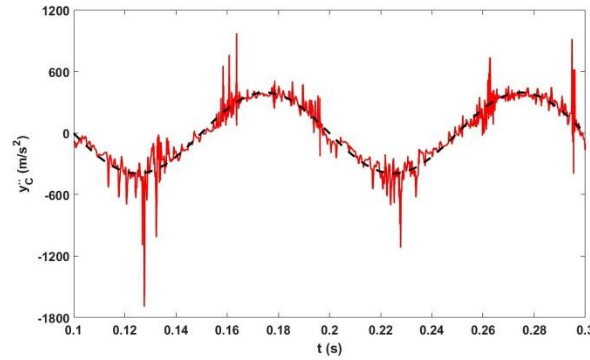
(a) C= 0.5 mm



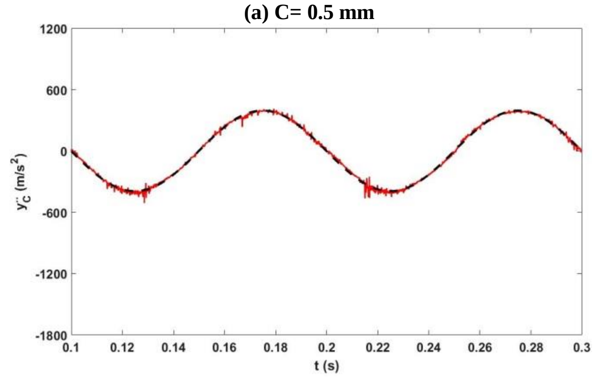
(b) C=0.00001 mm

Fig. 4 Linear acceleration of the EE in x direction without clearance: ▬ ▬ with clearance: ▬▬▬

As shown in these figures, the magnitude of clearance size obviously affects the end-effector acceleration. The manipulator experiences higher accelerations for the higher clearance sizes. Therefore, one can expect higher impact forces at the joints, if this is the case.

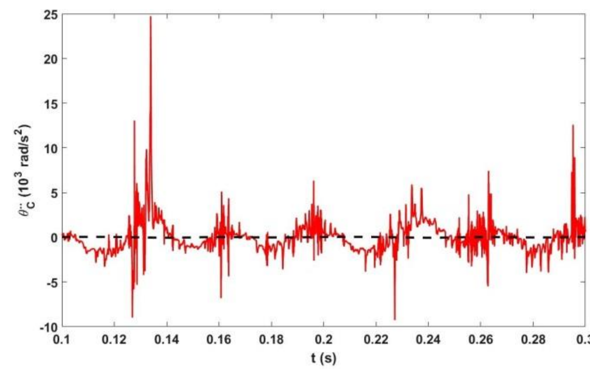


(a) C= 0.5 mm

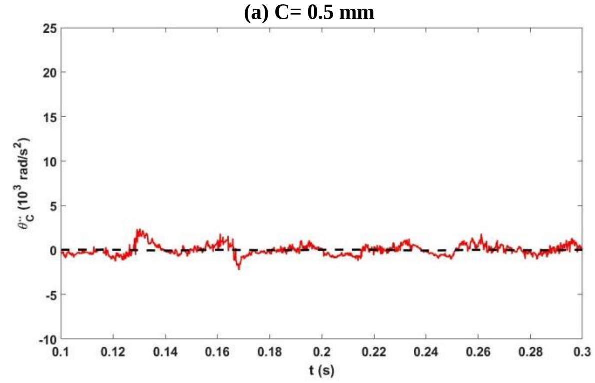


(b) C=0.00001 mm

Fig. 5 Linear acceleration of the EE in y direction without clearance: ▬ ▬ with clearance**:** ▬▬▬

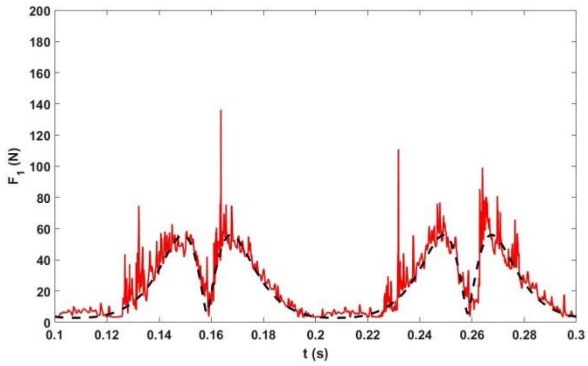


(a) C= 0.5 mm

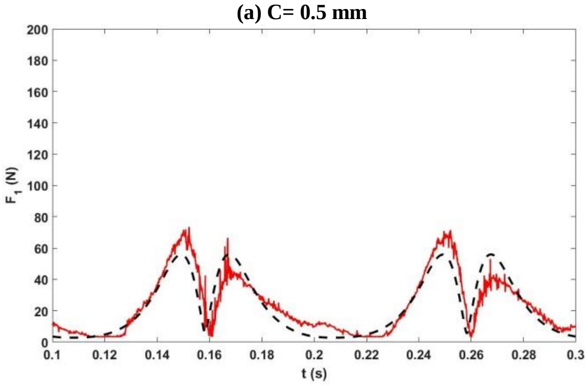


(b) C=0.00001 mm

Fig. 6 Angular acceleration of the EE without ▬ ▬ clearance: with clearance: ▬▬▬

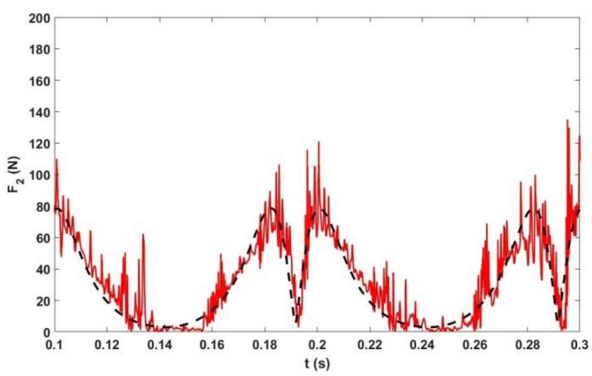


(a) C= 0.5 mm

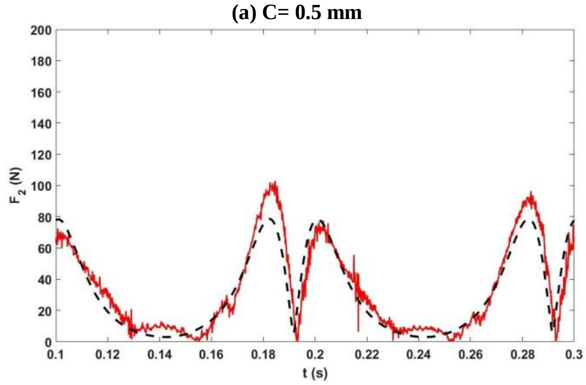


(b) C=0.00001 mm

Fig. 7 Actuation force of the first prismatic actuator without clearance: ▬ ▬ with clearance: ▬▬



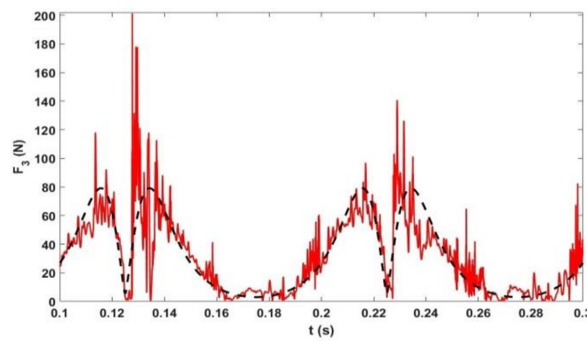
(a) C= 0.5 mm



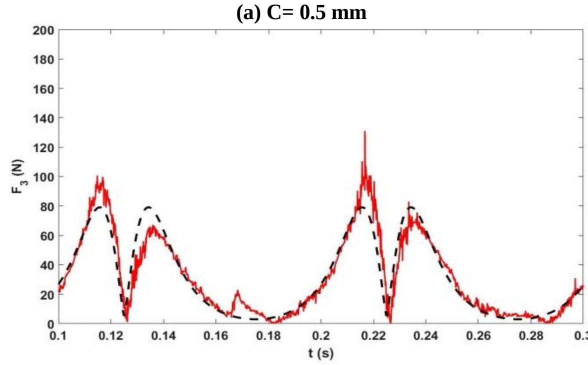
(b) C=0.00001 mm

Fig. 8 Actuation force of the second prismatic actuator without clearance: ▬ ▬ with clearance: ▬▬

The linear forces needed for three linear actuators are shown in Figs. 7-9 for different clearance sizes. As expected, the required forces experience sharp changes in the case of manipulator with clearance at the joints, while in the ideal case they are very smooth. Therefore, the bigger clearance size makes bigger linear actuators in the manipulator.



(a) C= 0.5 mm



(b) C=0.00001 mm

Fig. 9 Actuation force of the third prismatic actuator without clearance: ▬ ▬ with clearance: ▬▬

5 CONCLUSION

The work of the paper makes sense to engineering applications in multi-body dynamics. During the design process, important issues with respect to non-ideal joints should be investigated. In this study, dynamic modelling in ADAMS is presented and the software results are analysed. The dynamic behaviour of a planar 3-RPR parallel manipulator, in the presence of clearances in revolute joints, has been investigated. The results have revealed that the existence of joint clearance clearly affects the accelerations and input required forces. Numerical results have revealed that higher clearance sizes led to higher impulsive accelerations and higher forces in the joints. Finally, it has been concluded that the effects of joint clearance on the dynamic behaviour of mechanism should not be ignored while the robot dynamics is very sensitive to the magnitude of clearance size. The joint clearance influences the mechanism's performance and this paper shows what happens when the join clearance evolves and increased. The work of the paper makes sense to engineering applications. During the design process, important issues with respect to wear should be investigated. For example, if the material data with respect to the wear coefficients is known, what characteristics should materials of joint components present to withstand wear.

NOMENCALTURE

Latin symbols

C_{max}	Maximum value of the damping coefficient
C	Radial clearance
d_{max}	Maximum value of the Penetration
e	Eccentricity magnitude
E_i	Young's modulus of elasticity
F_n	Normal contact force
F_1	Actuation force of the first prismatic actuator
F_2	Actuation force of the second prismatic actuator
F_3	Actuation force of the third prismatic actuator
g	Distance between journal and bearing's centers
K	Stiffness
n	Hertz's contact force exponent
R_i	Bearing radius
R_j	Journal radius
x_{Ai}	Position of point A_i in x direction
x_C	Position of mass center of EE in x direction
$\ddot{x}_c$	Linear acceleration of the EE in x direction
x_{Ci}	Position of point C_i in x direction
y_{Ai}	Position of point A_i in y direction
y_C	Position of mass center of EE in y direction
$\ddot{y}_c$	Linear acceleration of the EE in y direction
y_{Ci}	Position of point C_i in y direction

Greek symbols

δ	Penetration depth
$\dot{\delta}$	Penetration velocity
θ_1	Angular position of first leg
θ_2	Angular position of second leg
θ_3	Angular position of third leg
φ	Angular position of EE
$\ddot{\theta}_c$	Angular acceleration of EE
ν_i	Poisson's ratio

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