

Effects of Input Speed on the Dynamic Response of Planar Multi-body Systems with Differently Located Frictionless Revolute Clearance Joints

Onesmus Muvengei, John Kihui and Bernard Ikua

Abstract—This paper numerically investigates the effects of input speed on the overall dynamic characteristics of a multi-body system with differently located revolute clearance joints without friction. A typical planar slider-crank mechanism is used as a demonstration case in which the effects of the input speed on the dynamic performance of the mechanism with a revolute clearance joint between the crank and connecting rod, and between the connecting rod and slider are separately investigated with comprehensive observations numerically presented. It is observed that, changing the driving speed of a multi-body system makes the behavior of the system to change from either periodic to chaotic, or chaotic to periodic depending on which joint has clearance. The location of the clearance revolute joint and the operating speed of a multi-body system play a crucial role in predicting accurately the dynamic responses of the system. Therefore the dynamic behavior of one clearance revolute joint cannot be used as a general case for a mechanical system.

Keywords—Chaotic behavior, Contact-impact forces, Dynamic response, Multi-body mechanical system, Periodic behavior, Poincaré maps, Quasi-periodic behavior, Revolute clearance joint

I. INTRODUCTION

THE dynamic modeling of multi-body systems is a key aid in the analysis, design, optimization, control, and simulation of mechanisms and manipulators. However, clearance, friction, impact and other phenomena associated with real joints have been routinely ignored in order to simplify the dynamic model. The increasing requirement for high-speed and precise machines, mechanisms and manipulators demands that the kinematic joints be treated in a realistic way. This is because in a real mechanical joint, a clearance which permits the relative motion between the connected bodies as well as the components assemblage, is always present. The clearance no matter how small it is, can lead to vibration and fatigue phenomena, premature failure and lack of precision or even random overall behavior.

There is a significant amount of literature available which discusses theoretical and experimental analysis of imperfect kinematic joints in a variety of planar and spatial mechanical systems with rigid or flexible links [1]–[37]. Many of these works focus on the planar systems in which only one kinematic joint is modeled as an imperfect joint [1], [2], [4]–[13], [15]–[18], [20]–[23], [26], [27], [30]–[35]. Although, the

results from such experimental and analytical models have been shown to provide important insights on the behavior of mechanical systems with imperfect joints, the models do not allow for study of the interactions of multiple kinematic imperfect joints. Furthermore a real mechanical system does not have only one real joint, but practically all joints are real. This led several researchers such as Flores (2004) [38] and Cheriyan (2006) [39] to strongly recommend for their work to be extended to include multi-body mechanical systems with multiple imperfect joints, and with a variety of joints such as prismatic and universal joints. Few recent papers by Erkaya and Uzmay (2009-2010) [19], [25], and by Flores (2010) [36] have considered the nonlinear dynamic analysis of multi-body systems with two imperfect joints. However in these research papers, only mechanisms with rigid links have been considered and the interaction effects of the imperfect joints on the overall response of a multi-body system were not investigated. Also, Erkaya and Uzmay (2009-2010) [19], [25] modeled the clearance in the journal bearing as a massless imaginary link whose length is equal to the clearance size. This assumption is not valid especially at large clearances because the journal and bearing will not be in contact at all times.

The primary objective of this research work therefore is to numerically quantify the influence of the driving speed on the dynamic characteristics of rigid-planar multi-body mechanical systems with differently located revolute clearance joints without friction. This work will provide inherent information which can be of great use in the analysis of multi-body systems with clearance joints especially as it regards to the effective design and control tasks of these systems. This study will also form a base towards the investigation of dynamic interaction of multiple revolute clearance joints in a multi-body mechanical system.

II. EQUATIONS OF MOTION OF MULTI-BODY SYSTEMS

In order to analyze the dynamic response of a multi-body system whether with ideal or real joints, it is first necessary to formulate the equations of motion that govern its behavior. The process of formulating the equations which govern the behavior of the system is called modeling the system, while the process of numerically solving the generated equations of motion in order to analyze the system's response is termed as simulation.

In computational kinematic and dynamic analysis of multi-body mechanical systems, a set of algebraic kinematic constraint equations which describe the joint connectivity between

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the bodies of the multi-body system are used. These kinematic constraint equations can be presented in terms of appropriate system of coordinates which allow one to clearly define at all times the position, velocity and acceleration of all bodies of the mechanical system.

The methodology adopted in this work to derive the dynamic equations of multi-body systems follows closely that of Nikravesh (1988) [40], in which the generalized Cartesian coordinates and the Newton-Euler's approach are utilized. In addition, the Baumgarte stabilization technique [41] is used to control the position and velocity violations during direct integration of the equations of motion. The methodology presented is implemented in a MATLAB code, which is capable of automatically generating and solving the equations of motion for the multi-body systems.

Computationally, the dynamic analysis of a multi-body mechanical system involves solving (1) numerically for $\ddot{\mathbf{q}}$ and λ [42]. Then, in each integration time step, the accelerations vector, $\ddot{\mathbf{q}}$, together with velocities vector, $\dot{\mathbf{q}}$ are integrated in order to obtain the system velocities and positions for the next time step. This procedure is repeated until the final analysis time is reached.

$$\begin{pmatrix} M & C_q^T \\ C_q & 0 \end{pmatrix} \begin{pmatrix} \ddot{\mathbf{q}} \\ \lambda \end{pmatrix} = \begin{pmatrix} Q_e \\ -(C_q \dot{\mathbf{q}})_q \dot{\mathbf{q}} - 2C_{qt} \dot{\mathbf{q}} - C_{tt} \end{pmatrix} \quad (1)$$

M is the mass matrix of the system, $\ddot{\mathbf{q}}$ is the vector of the system acceleration, Q_e is a vector containing the external forces which are known and λ is a vector containing Lagrange multipliers. The code developed in this work was able to derive automatically the overall matrices M , Q_e , Q_d , solve (1) for $\ddot{\mathbf{q}}$ and λ , and finally integrate the vector for velocity and acceleration to get the system positions and velocities for the next time step.

The system of the motion equations shown in (1) does not use explicitly the position and velocity equations associated with the kinematic constraints. This implies that during simulation, chances are that the original constraint equations will be violated. Due to simplicity and easiness of computational implementation, the Baumgarte Stabilization Method (BSM) was employed in this work to control the position and velocity constraint violations brought about by direct integration of (1).

The principle behind BSM is to damp out the acceleration constraint violations by feeding back the violations of the position and velocity constraints. Thus, by using the Baumgarte's approach, the equations of motion for a dynamic system subjected to holonomic constraints are represented as,

$$\begin{pmatrix} M & C_q^T \\ C_q & 0 \end{pmatrix} \begin{pmatrix} \ddot{\mathbf{q}} \\ \lambda \end{pmatrix} = \begin{pmatrix} Q_e \\ Q_d - 2\alpha\dot{C} - \beta^2 C \end{pmatrix} \quad (2)$$

where α and β are termed as feedback parameters which should be arbitrarily chosen.

In this work, Direct Integration Method (DIM) which involves conversion of the n second-order differential equations of motion into $2n$ first-order differential equations was employed. In DIM, once the second-order differential equations are converted to first-order differential equations, an integration numerical scheme is employed to solve the initial-value problem.

To convert the n second-order differential equations of motion into $2n$ first-order differential equations arrays y and \dot{y} were defined as,

$$y = \begin{pmatrix} q \\ \dot{q} \end{pmatrix}$$

$$\dot{y} = \begin{pmatrix} \dot{q} \\ \ddot{q} \end{pmatrix}$$

The reason for introducing the new vectors y and \dot{y} is that most numerical integration algorithms deal with first-order differential equations. The numerical integration is such that velocities and accelerations at time t , after integration process, yield positions and velocities at next time step, $t = t + \Delta t$.

A. Kinematic Model of a Revolute Joint with Clearance

In order to simulate a real revolute joint, its necessary to develop a mathematical model for the joint in the multi-body system. Figure 1 shows two bodies i and j connected with a revolute joint with clearance. Part of body i is the bearing while part of body j is the journal. $X_i Y_i$ and $X_j Y_j$ are the body coordinate systems, while XY is the stationary global coordinate system. P_i is the center of the bearing and P_j is the center of the journal at the given instant.

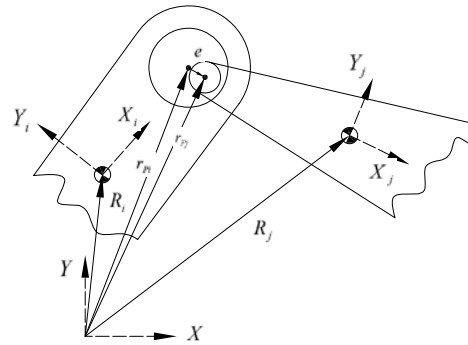


Fig. 1. Generic revolute joint with clearance

The eccentricity vector \vec{e} which connects the centers of the bearing and the journal is given as,

$$\begin{aligned} \vec{e} &= r_{P_j} - r_{P_i} \\ &= (R_j + A_j u_{P_j}) - (R_i + A_i u_{P_i}) \end{aligned} \quad (3)$$

where A_i and A_j are the transformation matrices of coordinates $X_i Y_i$ and $X_j Y_j$ respectively to coordinate XY , and u_{P_i} and u_{P_j} are the coordinates of centers of bodies i and j with respect to their coordinate systems.

The magnitude of the eccentricity vector is,

$$e = \sqrt{\vec{e}^T \vec{e}} \quad (4)$$

The penetration depth due to the impact between the journal and the bearing can be shown to be,

$$\delta = e - c \quad (5)$$

where c is the radial clearance at the joint which is the difference between the radius of the bearing (R_B) and the radius of the journal (R_J).

The contact points on bodies i and j during penetration are C_i and C_j respectively as shown in Fig. 2.

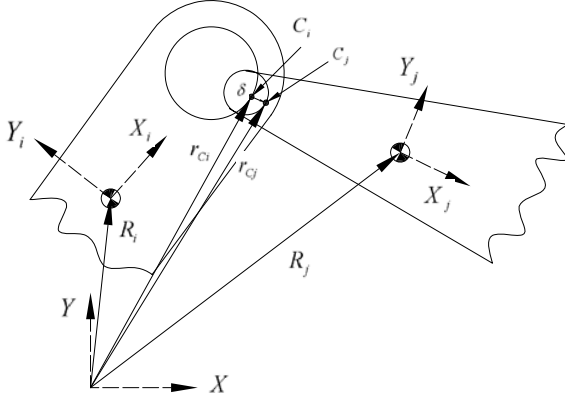


Fig. 2. Penetration depth due to impact between the bearing and the journal

The position of the contact points are given as,

$$r_{Ci} = R_i + A_i u_{Pi} + R_B \vec{n} \quad (6)$$

$$r_{Cj} = R_j + A_j u_{Pj} + R_J \vec{n} \quad (7)$$

where \vec{n} is the unit vector in the direction of penetration caused by the impact between the journal and the bearing, given as,

$$\vec{n} = \frac{\vec{e}}{e} \quad (8)$$

The velocity of the contact points in the global coordinate system is found by differentiating (6) and (7) with respect to time to get,

$$\dot{r}_{Ci} = \dot{R}_i + \dot{A}_i u_{Pi} + R_B \dot{\vec{n}} \quad (9)$$

$$\dot{r}_{Cj} = \dot{R}_j + \dot{A}_j u_{Pj} + R_J \dot{\vec{n}} \quad (10)$$

The components of the relative velocity of the contact points in the normal and tangential plane of collision are represented as \vec{v}_N and \vec{v}_T , and are given as,

$$\vec{v}_N = (\dot{r}_{Cj} - \dot{r}_{Ci}) \vec{n} \quad (11)$$

$$\vec{v}_T = (\dot{r}_{Cj} - \dot{r}_{Ci}) \vec{t} \quad (12)$$

where \vec{t} is obtained by rotating \vec{n} anticlockwise by 90° .

B. Dynamic Model of a Revolute Joint with Clearance

When the journal makes contact with the bearing, then impacts occur and contact-impact forces are created at the joint. Closer inspection of equation 5 shows that;

- When the journal is not in contact with the bearing, $e < c$ and the penetration has a negative value. In this case, the journal is in free-flight motion inside the bearing, and no impact-contact forces are created.

- When contact between the journal and the bearing is established, the penetration has a value equal or greater than zero. In this case, impact-contact forces at the joint are established.

Therefore the computational algorithm developed for dynamic analysis of a system with revolute clearance joint should ensure that impact-contact forces are applied when the depth of penetration is greater or equal to zero.

Since there are velocity components in the normal and tangential directions of the collision between the journal and the bearings as given in (11) and (12), then forces are generated in these two directions. The force normal to the direction of collision (F_N) can be evaluated using the contact force laws, such as Hertz, Lankarani-Nikravesh, Dubowsky-Freudenstein or ESDU-78035 contact models, while the force tangential to the direction of collision (F_T) which is the frictional force is evaluated using the appropriate frictional laws.

In this paper, it is assumed that no frictional forces are generated during the collision of the bearing and the journal, however friction will be included in further work. Since the direction of the normal unit vector \vec{n} is used as the working direction for the contact forces, then the contact forces at bodies i is;

$$F_{Ni} = F_N \vec{n} \quad (13)$$

From the Newton's third law of motion, the contact reaction force at body j will be,

$$F_{Nj} = -F_{Ni} \quad (14)$$

These forces which act at the contact points are transferred to the center of masses of bodies i and j as shown in Fig. 3. This transfer of forces from contact forces to the center of masses contributes to the moments given as,

$$M_i = (x_{Ci} - x_i) F_{NiY} - (y_{Ci} - y_i) F_{NiX} \quad (15)$$

$$M_j = (x_{Cj} - x_j) F_{NjY} - (y_{Cj} - y_j) F_{NjX} \quad (16)$$

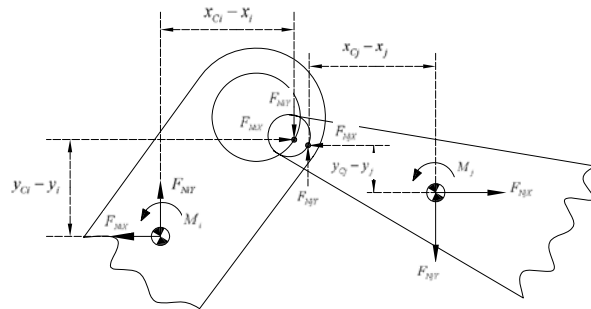


Fig. 3. Transfer of impact forces to the center of masses of the bodies

Once these forces and moments are known and added to the generalized vector of external forces Q_e in (2), then the description of the revolute joint with clearance is complete. No kinematic constraint was used when modeling the real joint, instead force constraints have been used.

C. Contact Force Laws

Once the journal makes contact with the bearing, forces normal to the direction of contact are created. In this work the nonlinear continuous contact force models between two colliding bodies will be used since they represent the physical nature of the contacting surfaces. These contact force models include; Hertz, Lankarani-Nikravesh, Dubowsky-Freudenstein and ESDU-78035 contact force models.

The Hertz law of contact relates the contact force as a nonlinear power function of the penetration depth as,

$$F_N = K\delta^n \quad (17)$$

where F_N is the normal contact force, δ is the penetration depth of the contacting bodies given in (5), exponent $n = 1.5$ for metallic surfaces and the generalized stiffness K which depends on the material properties and the shape of the contacting surfaces is given as;

$$K = \frac{4}{3(\sigma_1 + \sigma_2)} \left[\frac{R_1 R_2}{R_1 + R_2} \right]^{\frac{1}{2}} \quad (18)$$

where;

R_1 and R_2 are the radii of the spheres (the radius is negative for concave surfaces and positive for convex surfaces)

σ_1 and σ_2 are the material parameters given by;

$$\sigma_i = \frac{1 - \nu_i^2}{E_i} \quad \text{for } i = 1, 2$$

where E_i and ν_i are the Young's Modulus and Poisson's ratio associated with each sphere.

Unfortunately, the Hertz Law as given in (17) does not account for energy dissipation during the impact process and hence cannot be used in both phases of contact (compression and restitution). Lankarani and Nikravesh [44] extended the Hertz contact force model to include a hysteresis damping function to represent the energy dissipated during the impact. The authors separated the normal contact force given in (17) into elastic and dissipative components as;

$$F_N = K\delta^n + D\dot{\delta} \quad (19)$$

where $\dot{\delta}$ is the relative impact velocity given in (11), and D is the hysteresis coefficient given as;

$$D = \left[\frac{3K(1 - c_e^2)}{4\dot{\delta}^{(-)}} \right] \dot{\delta}^n \quad (20)$$

where $\dot{\delta}^{(-)}$ is the initial impact velocity. Therefore the final normal contact force can be expressed as;

$$F_N = K\delta^n \left[1 + \frac{3(1 - c_e^2)\dot{\delta}}{4\dot{\delta}^{(-)}} \right] \quad (21)$$

Equation (21) is only valid for impact velocities lower than the propagation velocity of elastic waves across the bodies, i.e., $\dot{\delta} \leq 10^{-5} \sqrt{\frac{E}{\rho}}$ where E is the Young's modulus and ρ is the material mass density [45].

The contact models given by (17) and (21) are applicable for colliding bodies with spherical contact areas. Various elastic models have been put forward for the cylindrical contact

surfaces, with the commonly used ones being the Dubowsky and Fruedenstein model and the ESDU-78035 model, both of which are given as (22) and (23) respectively;

$$\delta = F_N \left(\frac{\sigma_1 + \sigma_2}{L} \right) \left[\ln \left(\frac{L^3(R_1 - R_2)}{F_N R_1 R_2 (\sigma_1 - \sigma_2)} \right) + 1 \right] \quad (22)$$

and

$$\delta = F_N \left(\frac{\sigma_1 + \sigma_2}{L} \right) \left[\ln \left(\frac{4L(R_1 - R_2)}{F_N (\sigma_1 + \sigma_2)} \right) + 1 \right] \quad (23)$$

where L is the length of the cylinder. Equations (22) and (23) are nonlinear function for F_N and require an iterative scheme, such as Newton-Raphson method to solve for the normal contact force F_N for a known penetration depth δ . Also, these models do not account for energy dissipation during the impact process.

III. RESULTS AND DISCUSSIONS

This section contains extensive results obtained from computational simulations of a slider-crank mechanism with a revolute clearance joint. Two major cases are considered, that is;

- (a) Case 1: When revolute clearance joint only exist between the crank and the connecting rod.
- (b) Case 2: When revolute clearance joint only exist between the connecting rod and the slider.

This study takes into account two main functional parameters of the slider-crank mechanism, that is, the location of the considered clearance joint and the input crank speed.

A. Description of the Slider-Crank Mechanism

A typical slider-crank mechanism as shown in Fig. 4 is used as a demonstrative example to study the parametric effect of revolute joint clearance on the dynamic response of a multi-body mechanical system.

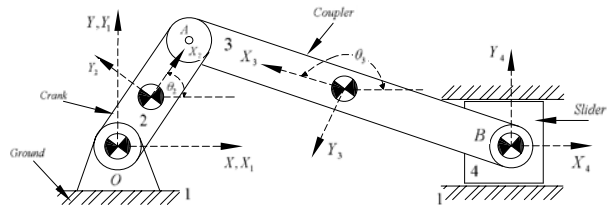


Fig. 4. Slider-crank mechanism

The slider-crank mechanism considered has the following parameters: Length of crank $LOA = 0.05m$, length of the coupler link $L_{AB} = 0.12m$, mass of the crank $m_2 = 0.3kg$, mass of the coupler $m_3 = 0.21kg$, mass of the slider $m_4 = 0.14kg$, moment of inertia of crank about its center of gravity, $I_2 = 0.00001kg.m^2$ and moment of inertia of coupler about its center of gravity, $I_2 = 0.00025kg.m^2$. In addition all the links are assumed to be uniform such that their centers of gravity are at their geometric centers. The following are other parameters used for the different contact models: Nominal bearing diameter $d=10mm$, Length of the cylindrical contact

between the journal and the bearing $L=20\text{mm}$, Coefficient of restitution $C_e=0.9$, Young's modulus $E=207\text{MPa}$, Poisson's ratio $\nu=0.3$ and integration time step $\Delta t=0.000001\text{s}$

In the simulations, the initial configuration of the mechanism is defined when the crank and the connecting rod are collinear, and the journal and the bearing centers of the considered clearance revolute joint to coincide. The initial positions and velocities necessary to start the dynamic simulation are obtained from kinematic simulation of the slider-crank mechanism in which all the joints are considered perfect.

The dynamic response of the slider-crank mechanism is presented by plotting the variations with time of the slider velocity, slider acceleration, reaction force at the clearance joint and torque required to maintain constant speed of the crank. The results are presented for four cycles of the mechanism after the first cycle when steady state is reached. The first cycle has instability due to the fact that the mechanism is moved from rest and because of the inertia, great impact occurs between the journal and the bearing of the revolute joint at the start of the simulation. The behavior of the revolute clearance joints is also illustrated by using the slider velocity and the slider acceleration to plot the Poincaré maps at different test scenarios.

B. Results for Different Contact Force Models

In this subsection, the dynamic responses of the slider-crank mechanism when joint A is separately modeled with 0.3mm clearance, and also when joint B is separately modeled with 0.3mm clearance using the four commonly known nonlinear contact laws.

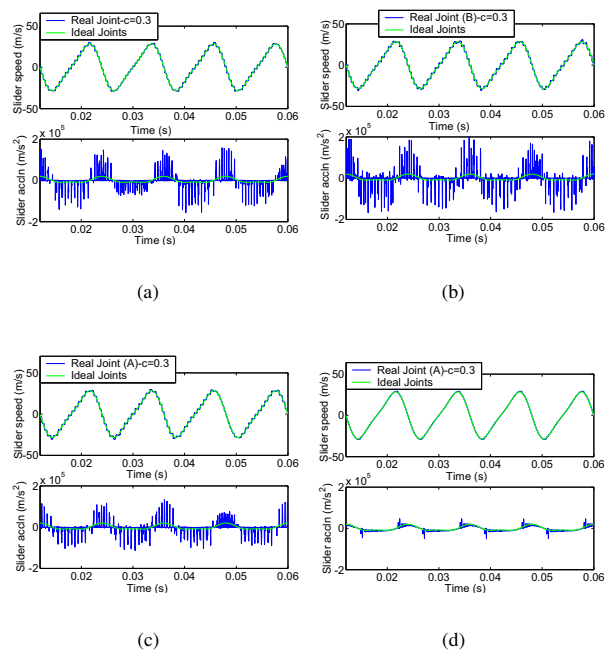


Fig. 5. Slider linear velocity and acceleration responses when revolute joint A is modeled with a 0.3mm clearance using (a) Hertz contact force law (b) Dubowsky-Freudensteins contact force law (c) ESDU-78035 contact force law and (d) Lankarani-Nikravesh contact force law

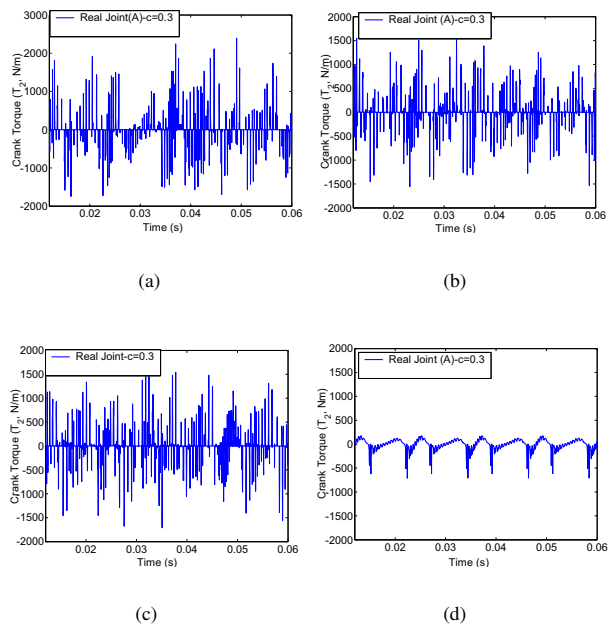


Fig. 6. Driving torque responses when revolute joint A is modeled with a 0.3mm clearance using (a) Hertz contact force law (b) Dubowsky-Freudensteins contact force law (c) ESDU-78035 contact force law and (d) Lankarani-Nikravesh contact force law

The influence of the joint clearance is clearly observed at

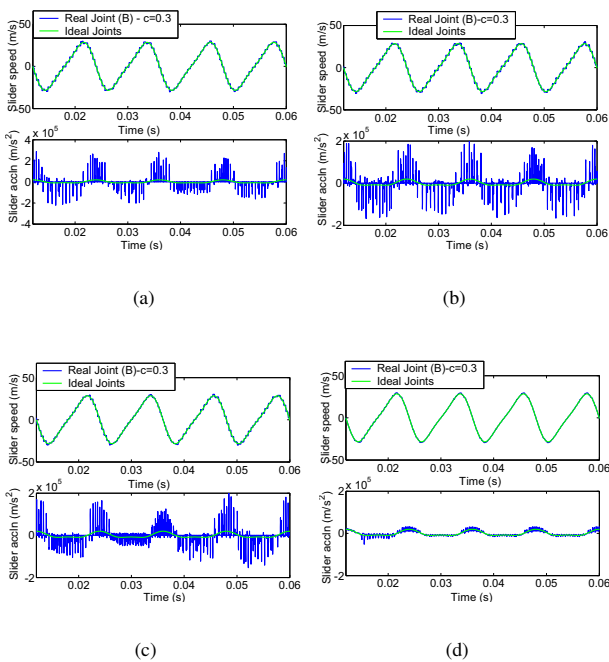


Fig. 7. Slider linear velocity and acceleration responses when revolute joint B is modeled with a 0.3mm clearance using (a) Hertz contact force law (b) Dubowsky-Freudensteins contact force law (c) ESDU-78035 contact force law and (d) Lankarani-Nikravesh contact force law

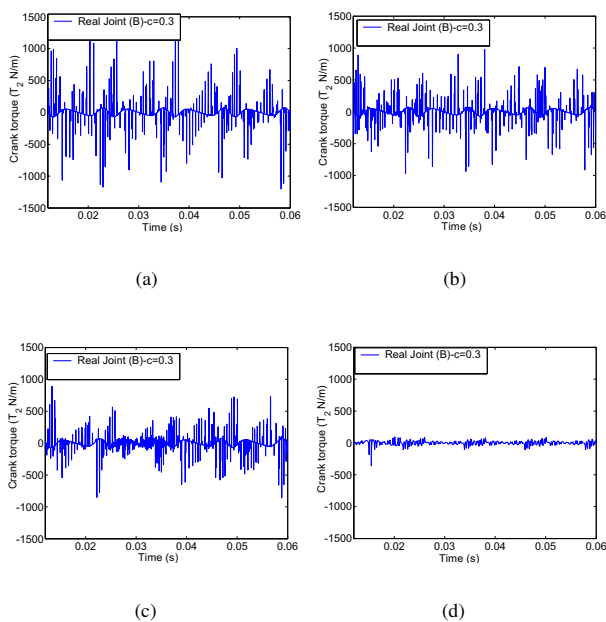


Fig. 8. Driving torque responses when revolute joint B is modeled with a 0.3mm clearance using (a) Hertz contact force law (b) Dubowsky-Freudensteins contact force law (c) ESDU-78035 contact force law and (d) Lankarani-Nikravesh contact force law

the stair-case shaped velocity curves. The horizontal lines in the velocity curves indicate that the journal is in free-flight motion inside the bearing, and the slider moves with a constant velocity. Sudden changes in velocity of the slider is due to impacts between the journal and the bearing. These impacts are also visible in the acceleration curves by high peak values. Also smooth changes in velocity are observed implying that the journal and the bearing are in continuous contact motion, that is, the journal follows the bearing wall. This situation is confirmed by the smooth changes in the acceleration curve.

The elastic contact models, that is, Hertz, Dubowsky-Freudensteins and ESDU-78035 contact models, which do not account for energy dissipation lead to high peaks for the slider acceleration and the torque required to drive the crank with a constant angular velocity. The continuous contact force model proposed by Lankarani and Nikravesh presents much lower slider acceleration and crank torque peaks, due to the dissipative energy features of the model. Such energy dissipation is also reflected at the slider velocity and acceleration curves by the long periods of time for which the journal and bearing are in continuous contact mode. There is no much difference between the three nonlinear elastic contact laws. This implies that the two cylindrical contact models (that is, Dubowsky-Freudensteins and ESDU-78035 contact models) do not present any advantage compared to the elastic spherical contact model (that is, the Hertz contact model). However, the cylindrical models are nonlinear and implicit functions, and therefore they require an iterative procedure such as Newton-Raphson algorithm to solve them which is computationally time consuming. The Hertz relation along with the modification to include the energy dissipation in the form of internal damping (that is, the Lankarani-Nikravesh model) has been adopted by many researchers and has proven to produce results which correlate well with the experimental ones. Therefore, in the preceding results, the model proposed by Lankarani and Nikravesh will be employed when modeling the contact-impact forces in a revolute clearance joint.

It is also observed that the slider acceleration peaks when Joint B is modeled as a real joint are higher than the acceleration peaks produced when Joint A is modeled as a real joint. In addition, the crank torques obtained when Joint A is modeled as a real joint have higher peaks as compared to the peaks of crank torques obtained when Joint B is modeled as a real joint. An explanation to these observations will be sought and made once such behaviors are validated experimentally.

C. Influence of the Input Crank Velocity

The range of the input crank speeds used at each joint is 800rpm, 1200rpm, 2500rpm and 5000rpm, and the radial clearance at each joint is 0.3mm. Figures 9(a) to 12(d) show the results when only Joint A is modeled as a clearance revolute joint, while Figs. 13(a) to 16(d) present the results when only Joint B is modeled as a clearance revolute joint.

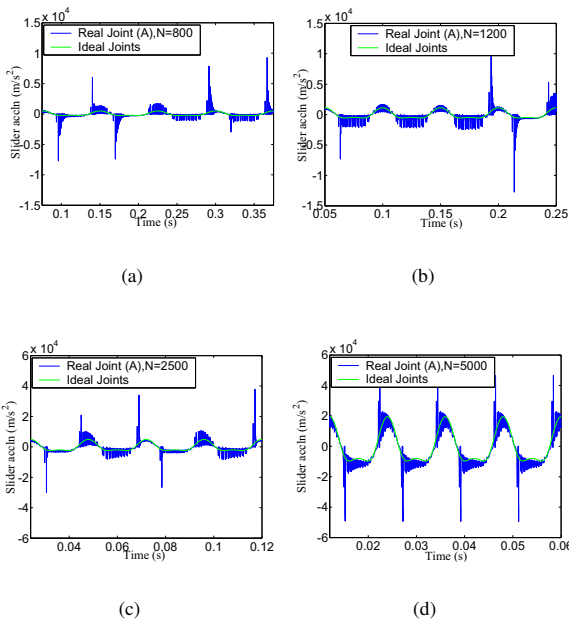


Fig. 9. Slider acceleration responses for 0.3mm clearance size at joint A for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm

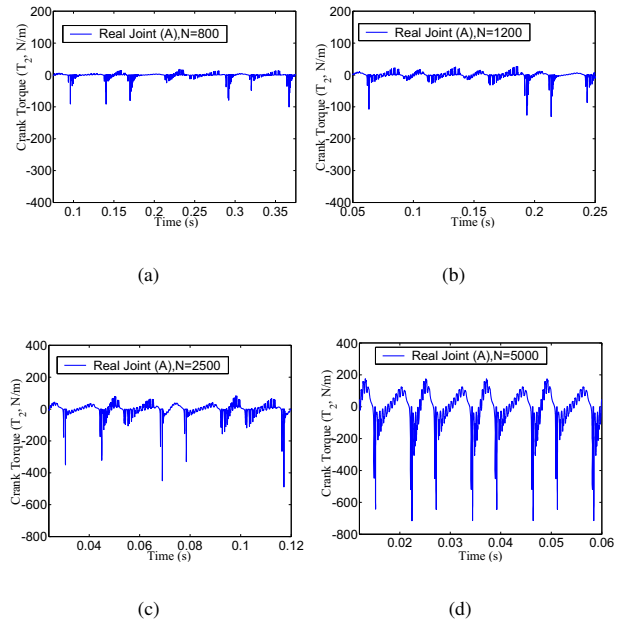


Fig. 11. Crank torque responses for 0.3mm clearance size at joint A for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm

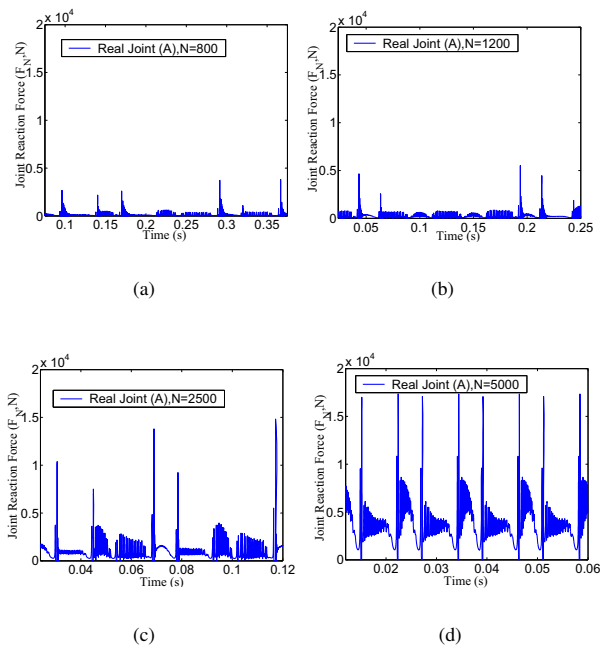


Fig. 10. Joint reaction force responses for 0.3mm clearance size at joint A for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm

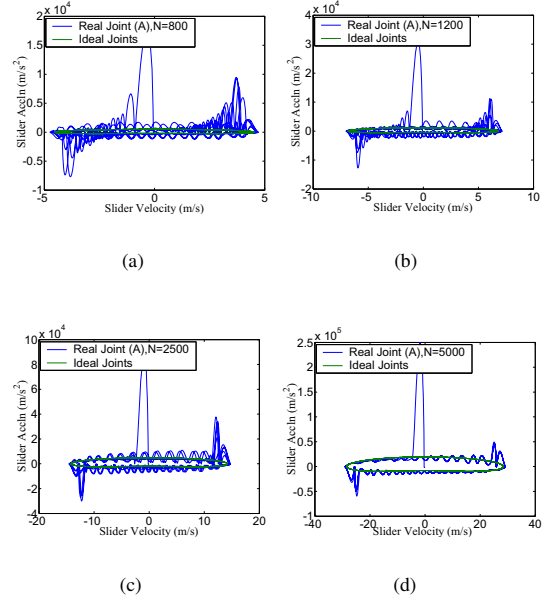
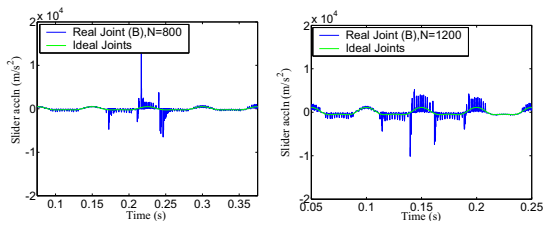


Fig. 12. Poincaré maps for 0.3mm clearance size at joint A for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm

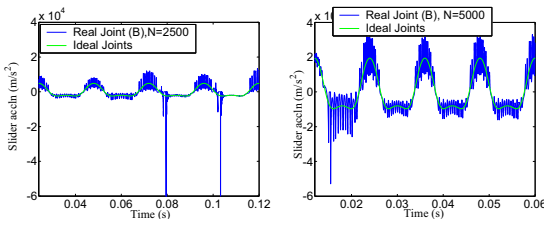
Figures 9(a) to 11(d) show that increasing the rotational speed of the crank, the mechanism experiences increased peaks of the slider acceleration, joint reaction force and the crank moment due to increased collisions between the journal and

the bearing of the clearance Joint A. However the Poincaré maps presented in Figs. 12(a) to 12(d) show that when the crank speed is increased from 800rpm to 5000rpm while holding the radial clearance of Joint A constant, the behavior of the system changes from chaotic to quasi-periodic, and then to periodic at a speed of 5000rpm.



(a)

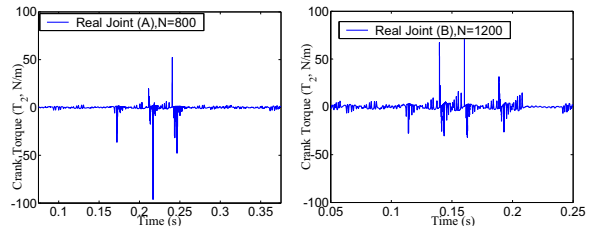
(b)



(c)

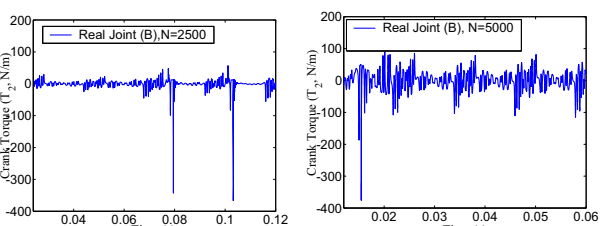
(d)

Fig. 13. Slider acceleration responses for 0.3mm clearance size at joint B for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm



(a)

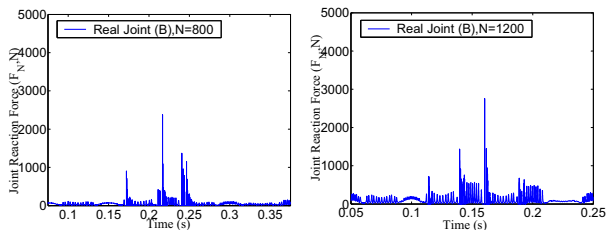
(b)



(c)

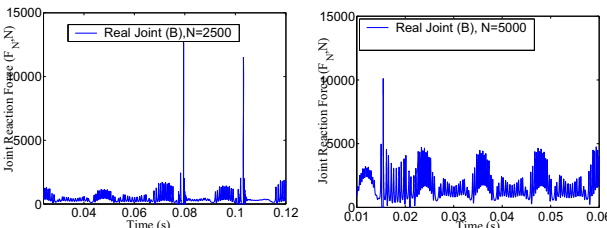
(d)

Fig. 15. Crank torque responses for 0.3mm clearance size at joint B for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm



(a)

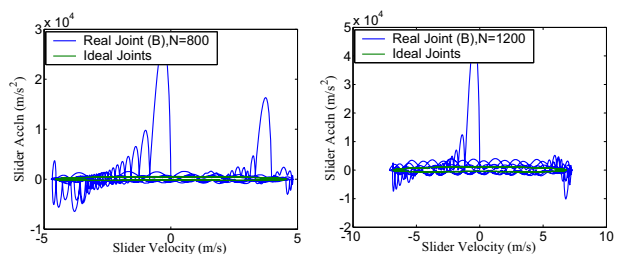
(b)



(c)

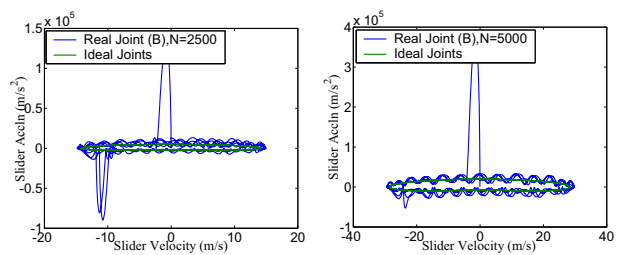
(d)

Fig. 14. Joint reaction force responses for 0.3mm clearance size at joint B for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm



(a)

(b)



(c)

(d)

Fig. 16. Poincaré maps for 0.3mm clearance size at joint B for different crank speeds (a) 800rpm (b) 1200rpm (c) 2500rpm (d) 5000rpm

Figures 13(a) to 15(d) show that increasing the rotational speed of the crank, the mechanism experiences increased peaks of the slider acceleration, joint reaction force and the crank moment due to collisions between the journal and the bearing of the clearance Joint B. However the Poincaré maps presented

in Figs. 16(a) to 16(d) show that when the crank speed is increased from 800rpm to 5000rpm while holding the radial clearance of Joint B constant, the behavior of the system changes from periodic to quasi-periodic and then to chaotic

at a speed of 5000rpm. This behavior is different from the one witnessed when only Joint A was modeled as a revolute clearance joint, in which the behavior changes from chaotic to periodic when the speed of the crank is increased as shown in Figs. 12(a) to 12(d). Although, the crank speed variations in the mechanism show almost the same effects on the dynamic response of the system with differently positioned clearance joints, a closer analysis shows that increasing the driving speed of a mechanism, the behavior of the mechanism may change from either periodic to chaotic, or chaotic to periodic depending on which joint has clearance. Therefore in order to design effective controllers for eliminating fully the chaotic behaviors brought about by the non-linearities of joints with clearances, the dynamic effect of each joint on the system should be understood, that is, the effects of driving speeds in one clearance joint cannot be used as a general case in a mechanical system.

IV. CONCLUSION

From the numerical simulations presented in this work, it can be concluded that the dynamic response of a multi-body mechanical system with revolute clearance joint depends on the location of the joint and the operating speed of the system. It is clear that the operating speed of the multi-body mechanical system affects significantly the dynamic response of a system with revolute clearance joint. The higher the operating speed, the higher the impact forces at the clearance joint. However, increasing the driving speed of a multi-body mechanical, the behavior of the mechanism may change from either periodic to chaotic, or chaotic to periodic depending on which joint has clearance. Therefore in order to design effective controllers for eliminating fully the chaotic behaviors brought about by the non-linearities of joints with clearances, the dynamic effect of each joint on the system should be understood. This is because the effects of the driving speeds in one clearance joint cannot be used as a general case in a mechanical system.

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REFERENCES

- [1] Dubowsky, S. and Freudenstein, F., "Dynamic analysis of mechanical systems with clearances, part 1: Formulation of dynamic model," *Journal of Engineering for Industry*, vol. 93(1), pp. 305–309, 1971.
- [2] Dubowsky, S. and Freudenstein, F., "Dynamic analysis of mechanical systems with clearances, part 2: Dynamic response," *Journal of Engineering for Industry*, vol. 93(1), pp. 310–316, 1971.
- [3] Dubowsky, S., Deck, J. F. and Costello, H., "The dynamic modeling of flexible spatial machine systems with clearance connections," *Journal of Mechanisms, Transmissions and Automation in Design*, vol. 109, pp. 87–94, 1987.
- [4] Earles, S.W.E. and Wu, C.L.S., "Motion analysis of a rigid link mechanism with clearance at a bearing using lagrangian mechanics and digital computation," *Journal of Mechanisms*, pp. 83–89, 1973.
- [5] Wu, C.L.S. and Earles, S.W.E., "A determination of contact-loss at a bearing of a linkage mechanism," *Journal of Engineering for Industry*, vol. 99(2), pp. 375–380, 1977.
- [6] Furuhashi, T., Morita, N. and Matsuura, M., "Research on dynamics of four-bar linkage with clearances at turning pairs 1st report: General theory using continuous contact model," *JSME*, vol. 21, pp. 518–523, 1978.
- [7] Furuhashi, T., Morita, N. and Matsuura, M., "Research on dynamics of four-bar linkage with clearances at turning pairs 2nd report: Analysis of crank-lever mechanism with clearance at joint of coupler and lever using continuous contact model," *JSME*, vol. 21, pp. 1284–1291, 1978.
- [8] Furuhashi, T., Morita, N. and Matsuura, M., "Research on dynamics of four-bar linkage with clearances at turning pairs 3rd report: Analysis of crank-lever mechanism with clearance at joint of coupler and lever using continuous contact model," *JSME*, vol. 21, pp. 1292–1298, 1978.
- [9] Furuhashi, T., Morita, N. and Matsuura, M., "Research on dynamics of four-bar linkage with clearances at turning pairs 4th report: Forces acting at joints of crank-lever mechanism," *JSME*, vol. 21, pp. 1292–1298, 1978.
- [10] Farahanchi, F. and Shaw, S. W., "Chaotic and periodic dynamics of a slider-crank mechanism with slider clearance," *Journal of Sound and Vibration*, vol. 177(3), pp. 307–324, 1994.
- [11] Rhee, J. and Akay A., "Dynamic response of a revolute joint with clearance," *Journal of Mechanisms and Machine Theory*, vol. 31(1), pp. 121–134, 1996.
- [12] Ravn, P., "A continuous analysis method for planar multibody systems with joint clearance," *Journal of Multibody System Dynamics*, vol. 2, pp. 1–24, 1998.
- [13] Ravn, P., Shivaswamy, S., Alshaer, B. J. and Lankarani, H. M., "Joint clearances with lubricated long bearings in multibody mechanical systems," *Journal of Mechanical Design*, vol. 122, pp. 484–488, 2000.
- [14] Chunmei, J., Yang, Q., Ling, F. and Ling, Z., "The nonlinear dynamic behavior of an elastic linkage mechanism with clearances," *Journal of Sound and Vibration*, vol. 249(2), pp. 213–226, 2002.
- [15] Chang, Z., "Nonlinear dynamics and analysis of four-bar linkage with clearance," in *In Proceedings of 12th IFToMM Congress, France*, 2007.
- [16] Schwab, A.L., Meijaard, J.P. and Meijers, P., "A comparison of revolute joint clearance models in the dynamic analysis of rigid and elastic mechanical systems," vol. 37, pp. 895–913, 2002.
- [17] Flores, P., Ambrosio, J., Claro, J.P., "Dynamic analysis for planar multibody mechanical systems with lubricated joints," *Journal of Multibody Systems Dynamics*, vol. 12, pp. 47–74, 2004.
- [18] Flores, P., and Ambrosio, J., "Revolute joints with clearance in multibody systems," *Journal of Computers and Structures*, vol. 82, pp. 1359–1369, 2004.
- [19] Erkaya, S., and Uzmay, I., "Experimental investigation of joint clearance effects on the dynamics of a slider-crank mechanism," *Journal of Multibody System Dynamics*, vol. 24, pp. 81–102, 2010.
- [20] Shiau, T.N., Tsai, Y.J., Tsai, M.S., "Nonlinear dynamic analysis of a parallel mechanism with consideration of joint effects," *Journal of Mechanism and Machine Theory*, vol. 43, pp. 491–505, 2008.
- [21] Erkaya, S. and Uzmay, I., "A neural-genetic (nn-ga) approach for optimising mechanisms having joints with clearance," *Journal of Multibody Systems Dynamics*, vol. 20, pp. 69–83, 2008.
- [22] Erkaya, S., and Uzmay, I., "Determining link parameters using genetic algorithm in mechanisms with joint clearance," *Journal of Mechanisms and Machine Theory*, vol. 44, pp. 222–234, 2009.
- [23] Erkaya, S., and Uzmay, I., "Optimization of transmission angle for slider-crank mechanism with joint clearances," *Journal of Structural Multidiscipline Optimization*, vol. 37, pp. 493–508, 2009.
- [24] Khemili, I., and Romdhane, L., "Dynamic analysis of a flexible slider-crank mechanism with clearance," *European Journal of Mechanics, Elsevier*, vol. 27, pp. 882–898, 2008.
- [25] Erkaya, S., and Uzmay, I., "Investigation on effect of joint clearance on dynamics of four-bar mechanism," *Journal of Nonlinear Dynamics*, vol. 58, pp. 179–198, 2009.
- [26] Liu, T. S. and Lin, Y. S., "Dynamic analysis of flexible linkages with lubricated joints," *Journal of Sound and Vibration*, vol. 141, pp. 193–205, 1990.

- [27] Ravn, P., Shivaswamy, S. and Lankarani, H. M., "Treatment of lubrication in long bearings for joint clearances in multibody mechanical systems," in *Proceedings of the ASME Design Technical Conference*, Las Vegas, September 12-15 1999.
- [28] Olivier, A. B. and Rodriguez, J., "Modeling of Joints with Clearance in Flexible Multibody Systems," *International Journal of Solids and Structures*, vol. 39, pp. 41–63, 2002.
- [29] Kakizaki, T., Deck, J.F. and Dubowsky, S., "Modeling the spatial dynamics of robotic manipulators with flexible links and joint clearances," *Journal of Mechanical Design*, vol. 115, pp. 839–847, 1993.
- [30] Jia, X., Jin, D., Ji, L., and Zhang, J., "Investigation on the dynamic performance of the tripod-ball sliding joint with clearance in a crank-slider mechanism. part 1. theoretical and experimental results.," *Journal of Sound and Vibrations*, vol. 252(5), p. 919933, 2002.
- [31] Bing, S. and Ye, J., "Dynamic analysis of the reheat-stop-valve mechanism with revolute clearance joint in consideration of thermal effect.," *Journal of Mechanisms and Machine Theory*, vol. 43(12), pp. 1625–1638, 2008.
- [32] Flores, P., "Modeling and simulation of wear in revolute clearance joints in multibody systems," *Journal of Mechanisms and machine Theory*, vol. 44(6), pp. 1211–1222, 2009.
- [33] Dupac, M. and Beale, D.G., "Dynamic analysis of a flexible linkage mechanism with cracks and clearance." To be published in *Journal of Mechanisms and Machine Theory*, 2010.
- [34] Flores, P., Ambrsio, J., Claro, J.C.P., Lankarani, H.M. and Koshy, C.S., "Lubricated revolute joints in rigid multibody systems," *Journal of Nonlinear Dynamics*, vol. 56(3), pp. 277–295, 2009.
- [35] Mukras, S., Kim, N.H., Mauntler, N.A., Schmitz, T.L., and Sawyer, W.G., "Analysis of planar multibody systems with revolute joint wear," *Journal of Wear*, vol. 268, pp. 643–652, 2010.
- [36] Flores, P., "A parametric study on the dynamic response of planar multibody systems with multiple clearance joints," *Journal of Nonlinear Dynamics*, vol. 4, pp. 633–653, 2010.
- [37] Dubowsky, S., and Moening, M.F., "An Experimental and Analytical Study of Impact Forces in Elastic Mechanical Systems with Clearances," *Journal of Mechanism and Machine Theory*, vol. 13, pp. 451–465, 1978.
- [38] Flores, P., *Dynamic Analysis of Mechanical Systems with Imperfect Kinematic Joints*. PhD thesis, UNIVERSIDADE DO MINHO PARA, 2004.
- [39] Cheriyan, S. K., *Chracterization of Mechanical Systems with Real Joints and Flexible Links*. PhD thesis, Wichita State University, 2006.
- [40] Nikravesh, P.E., *Computer-Aided Analysis of Mechanical Systems*,. Prentice Hall, Englewood Cliffs, New Jersey, 1988.
- [41] Baumgarte, J., "Stabilization of constraints and integrals of motion in dynamical systems," *Journal of Computer Methods in Applied Mechanics and Engineering*, vol. 1, pp. 1–16, 1972.
- [42] Shabana, A. A., *Computational Dynamics*. John Wiley & Sons, New York, 1994.
- [43] Lankarani, H. M. and Nikravesh, P. E., "Continuous contact force models for impact analysis in multibody systems," *Journal of Nonlinear Dynamics*, pp. 194–207, 1994.
- [44] Lankarani, H.M., and Nikravsh, P.E., "A contact force model with hysteresis damping for impact analysis of multibody systems," *Journal of Mechanical Design*, vol. 112, pp. 369–376, 1990.
- [45] Love, A. E., *A treatise on the Mathematical Theory of Elasticity*. Dover Publishers, 4th ed., 1944.