Contact Impact Modelling In Revolute Joints with Clearance : A Dynamic Analysis

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Abstract: Revolute joints play a fundamental role in multibody mechanical systems, including robotic assemblies, internal combustion engines, and linkage mechanisms, by enabling relative rotational motion between connected parts. In real engineering practice, a small amount of clearance inevitably exists between the journal and bearing surfaces because of manufacturing tolerances, material wear, lubrication needs, and assembly inaccuracies. The existence of this clearance can cause repeated contact and separation between the mating components during operation. Such interactions introduce complex nonlinear dynamic responses, which may manifest as vibration, noise generation, elevated stress levels, and a reduction in positioning accuracy as well as component lifespan. Conventional dynamic analyses frequently assume perfectly constrained joints without clearance, which limits their ability to represent the actual behavior of mechanical systems under operating conditions.

The present research is concerned with establishing a dynamic contact–impact model for revolute joints that include clearance, with the objective of improving the understanding of surface interaction during motion. The study specifically examines the influence of important system parameters, including the magnitude of clearance, contact stiffness, damping characteristics, and rotational velocity, on the dynamic response of the joint. A mathematical representation describing the contact and separation behavior between the journal and bearing elements is formulated using recognized contact mechanics principles. Numerical simulation techniques are then applied to determine variations in contact force, frequency of impacts, vibration response, and the motion path of the journal center.

The outcomes of this investigation are expected to enhance the understanding of nonlinear dynamic characteristics associated with revolute joints operating with clearance. These findings can support improved mechanical design by reducing undesirable phenomena such as excessive vibration, surface wear, and operational instability. In addition, the developed modeling approach may serve as an effective predictive tool for evaluating joint performance and increasing the reliability and durability of mechanical systems functioning under practical working environments.

Keywords: Clearance size, Contact stiffness, Damping Coefficient , Journal Bearing ,Revolute joint

I. INTRODUCTION

Revolute joints are fundamental to mechanical systems ranging from robotics to heavy machinery. While appearing simple, the physical reality inside these joints involves complex interactions between clearances, surface roughness, and dynamic loads. These factors generate intermittent contact and impact forces that drive vibration, wear, and noise. In modern high-speed engineering, predicting these transient forces is essential for ensuring system reliability and precision.

While ideal joints would transmit motion smoothly, manufacturing tolerances and operational wear introduce clearances that lead to discontinuous contact. Although researchers have progressed from rigid-link assumptions to advanced Hertzian and viscoelastic models, a persistent gap remains. Existing formulations often struggle to balance high physical fidelity (e.g., nonlinear friction and lubrication) with the computational efficiency required for real-time simulation or design optimization. Inaccurate modelling leads to underestimated stress concentrations and positioning errors, compromising safety-critical applications in aerospace and industrial automation.

This study addresses this deficiency by developing an integrated contact impact model that combines realistic nonlinear dynamics with computational efficiency. By linking local contact mechanics—including elastic deformation and energy dissipation—with system-level multibody motion equations, the proposed approach provides a faithful representation of real-world operating conditions.

Research Objectives

1. **Develop** a mathematical model accounting for clearance, nonlinear stiffness, damping, and friction.
2. **Analyze** the dynamic response of systems under repeated joint impacts.
3. **Evaluate** the influence of clearance size, material properties, and rotational speed on stability.
4. **Validate** the model against established theoretical and experimental benchmarks.
5. **Provide** design insights to extend service life and reduce mechanical vibration.

Significance and Structure Accurate modelling reduces maintenance costs and supports predictive strategies for safer, more efficient manufacturing. This paper establishes the research territory, identifies the limitations of current niche models, and occupies that niche by detailing a new, balanced modelling approach.

operational lifespan, performance, and reliability. The results of this study will help create stronger frameworks for detecting faults, which will improve industrial maintenance procedures and guarantee increased system effectiveness.

II. Literature Review

The dynamic behavior of revolute joints with clearance has been widely investigated due to its significant influence on the performance and reliability of multibody mechanical systems. Researchers have consistently demonstrated that the presence of clearance introduces intermittent contact and impact between the journal and bearing surfaces, resulting in nonlinear dynamic effects such as vibration, wear, and loss of motion accuracy. Understanding these effects requires reliable contact force models capable of capturing the complex interaction between contacting surfaces during operation.

Bai et al. (2022) focused on the wear characteristics of revolute joints with clearance in mechanical systems. Their work developed numerical framework combining the Lankarani–Nikravesh contact force model with Archard's wear model to predict wear depth in joints. A slider–crank mechanism was used as representative system for analysis. This showed wear distribution is unevenly distributed across the contact surfaces and increases as the clearance increases ,operating speed increases or contact stiffness decreases. These observations demonstrate the direct influence of joint parameters on component durability and highlighting the importance of reliable modelling for predicting the long term performance.

Li and Qua , proposed a continuous contact force formulation for evaluating planar revolute joints with clearance. Their contribution addressed shortcomings associated with traditional models such as the Hertz and Winkler models, where parameters depend on empirical estimation. The proposed method utilized geometric compatibility conditions together with elastic half space theory to determine elastic response while damping characteristics were obtained through parameter identification techniques. Both simulation and experimental comparisons confirmed that the model provided more accurate estimation of impact behavior and energy dissipation across different operating scenarios. This contribution offered a structured procedure for determining model parameters and improving the precision of dynamic simulations.

Peng and co-workers explored how contact properties affect the motion characteristics of planar mechanisms equipped with lubricated revolute joints. Their formulation incorporated frictional forces and lubrication effects by combining elastic contact analysis with hydrodynamic lubrication theory impact forces and stabilizing system motion. In particular, the presence of an oil film was shown to generate supporting forces that minimize direct contact between joint components, resulting in reduced vibration and improved motion stability. These findings underline the importance of lubrication conditions in determining the dynamic behavior and reliability of revolute joints.

In addition to lubrication, surface condition has been identified as

an important factor influencing contact mechanics. Li et al.

introduced a contact force formulation based on fractal concepts to represent the effect of surface roughness in revolute joints. The model accounted for multiple deformation regimes, including elastic, elastic–plastic, and fully plastic contact stages.

Simulation outcomes showed that variations in surface texture significantly modify contact stiffness and impact intensity, especially in dry friction environments. The study concluded that incorporating surface micro-geometry into contact analysis enhances predictive capability compared with conventional simplified models.

Similarly, Lu et al. (2020) presented a probabilistic modeling framework to evaluate the dynamic performance of planar mechanisms with joint clearance. Their approach considered variability in system parameters such as surface roughness and material characteristics, enabling a more realistic representation of practical operating conditions. The results suggested that smoother contact surfaces tend to produce larger contact forces and shorter impact durations. Furthermore, the stochastic modeling strategy improved the robustness and reliability of predicted system responses. This research highlighted the importance of accounting for uncertainty during mechanical system design.

A detailed three-dimensional analytical formulation for revolute joints with clearance was later introduced by Marques and colleagues. Their work derived equations to identify contact locations, penetration depth, and relative motion during collision events. Contact forces were evaluated using classical Hertzian contact theory combined with a Coulomb friction model to simulate realistic interaction behavior. The analysis demonstrated that clearance substantially modifies system motion, leading to nonlinear response characteristics, higher vibration levels, and increased acceleration peaks compared with idealized joints. The study provided important insights into the behavior of spatial mechanisms and reinforced the necessity of accurately representing clearance effects in dynamic modeling.

III. RESEARCH GAP

Research on revolute joints with clearance has provided valuable insights into their dynamic response and operational behavior. Nevertheless, a large portion of the available literature examines individual aspects—such as wear mechanisms, lubrication conditions, or surface characteristics—without simultaneously considering the combined influence of multiple governing factors. Only a limited number of studies attempt to incorporate key parameters, including clearance magnitude, contact stiffness, damping characteristics, and rotational speed, within a unified analytical framework.

In addition, several existing models involve highly detailed mathematical formulations or demand significant computational resources, which can restrict their suitability for routine engineering analysis and practical system design. This situation highlights a noticeable gap between theoretical model development and its direct applicability in industrial environments.

Accordingly, there is a clear requirement for a computationally efficient and practically implementable modeling strategy capable of representing nonlinear contact–impact behavior without excessive numerical complexity. The present work addresses this requirement by proposing an integrated modeling approach that evaluates the combined effects of multiple system parameters and delivers consistent predictions under realistic operating scenarios

IV. METHODOLOGY

This investigation uses a systematic computational approach to study the dynamic behaviour of revolute joints with clearance, with particular focus on contact-impact phenomenon.

1. Literature Review and Foundation

The first stage involves reviewing existing studies on multibody dynamics and revolute joints. This helps in understanding the fundamental forces involved and in identifying suitable mathematical models already used by researchers to describe how components interact and collide.

2. Development of the Joint Model

A detailed computational model of the revolute joint is developed. Unlike an ideal joint with perfect fitting, this model includes a clearance or gap. This allows the inner element (journal) to move within the outer element (bearing), which is necessary to simulate real operating conditions where impacts occur.

3. Modelling Contact Forces

This stage focuses on defining the interaction between the contacting parts. Mathematical models such as the Lankarani–Nikravesh and Hertz contact models are used to determine:

- Normal force: The reaction force generated during impact
- Damping: The loss of energy during collision
- Friction: The resistance due to sliding between surfaces

4. Dynamic Simulation

The complete model is implemented in simulation software like MATLAB or MSC ADAMS. Simulations are carried out over a specific time duration to analyse joint motion under different conditions. Time-stepping methods are used to capture small and rapid vibrations caused by repeated impacts.

5. Parametric Analysis

To evaluate the influence of different factors, parameters are varied one at a time and simulations are repeated. The parameters considered include:

- Size of the clearance gap
- Operating speed of the joint
- Material stiffness

This helps in identifying which factors contribute most to vibration and wear.

6. Analysis of Results

In revolute clearance joints, wear occurs due to repeated contact and relative motion between the journal and bearing surfaces. For numerical analysis, Archard’s wear model is commonly used. This model relates wear volume to parameters such as applied load, sliding distance, and material hardness.

The model is expressed as:

$$V = K\frac{F_n \cdot s}{H}$$

where:

- V = wear volume
- s = sliding distance
- K = dimensionless wear coefficient

- F_n = normal contact force
- H = material hardness

This formula shows the relationship between the wear volume and the relative sliding distance, normal contact force as well the hardness of softer materials. In real engineering, the wear depth of the joint is widely used. In order to obtain the wear depth during the wear process, assume that the actual contact area is A, Archard's wear model of Equation (12)
can be written as

$$\frac{V}{As} = \frac{h}{s} = kp$$

where h is the wear depth; p is the contact pressure, which is expressed as linear wear coefficient and is expressed as k = KH
.
In the motion of mechanisms with clearance joints, the contact point of joints keeps changing, and the contact force and sliding distance are different in different moments. It means the sliding distance and contact stress between the journal and bearing changes with time during the motion of mechanism. The wear process is considered to be a dynamic process. Further, Archard's wear model of Equation (13) is expressed as the following differential form in

$$\frac{dh}{ds} = kp$$

Because the sliding distance between journal and bearing is always changing with the motion of mechanical system, the sliding speed of the contact point which is easier to measure is used to calculate the sliding distance. Consequently, the dynamic wear depth in Equation (14) is expressed as

$$dh = kpvdt$$

where v is the sliding speed.
The sliding velocity v can be obtained by the rotational speed between journal and bearing in the clearance joints. the rotational speed of the journal relative to the bearing is expressed as

$$\omega_{12} = \omega_1 \mp \omega_2$$

where ω1 and ω2 are the rotational speeds of bearing and journal, respectively.

Further, the sliding speed v at contact point between journal and bearing is expressed as

$$v = (R_J + \delta)\omega_{12} = (R_J + \delta)(\omega_1 \mp \omega_2)$$

where RJ is the diameter of the journal. Further, for any given time t, the wear depth at contact points of revolute clearance joints is calculated as

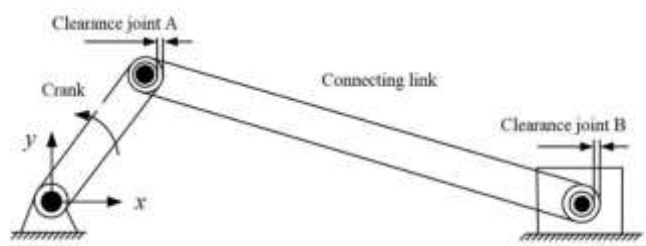
1. Computational Strategy of Wear Analysis for Clearance Joints

In order to analyze the wear characteristics in clearance joints of mechanisms, two main steps are presented, which are: dynamics analysis of mechanisms with clearances, and wear analysis of clearance joints. Firstly, the dynamics characteristics of mechanisms with clearances are analyzed. The contact forces of clearance joints and the sliding velocity between the journal and bearing are obtained. Secondly, the wear depth of clearance joints is calculated based on the dynamic wear model of . The detailed wear analysis process is shown as Figure 3 and performed as following:

- Establish the contact force models of the clearance joint, including the normal contact force model and the tangential friction force model; Establish the dynamics model and perform the dynamic simulation of mechanical system with joint clearances;
- Dynamics analysis and draw the contact force in the clearance joint as well as the relative sliding speeds between journal and bearing of the clearance joint;
- Calculate the wear depth of the clearance joint based on the dynamic Archard's wear model.
- Analyze and discuss the wear characteristics of the clearance joint for mechanisms in different case studies

Numerical Example and Results:

In this section, a planar slider-crank mechanism with two revolute clearance joints is use to represent the investigation.



Parameter	Value
Linear wear coefficient	2×10^{-8} m²/N
Contact pressure	1.5×10^{6}Pa
Sliding velocity	0.4 m/s
Time step	1s

Results :

The dynamic and tribological characteristics of the revolute clearance joint were examined under gradually increasing operating conditions. The numerical findings show that parameters such as contact force, sliding velocity, contact pressure, wear depth, and radial clearance are closely related to each other and strongly influence the overall behavior of the mechanism. During the analysis period, the contact force increased steadily from 120 N to 270 N, while the sliding velocity rose from 0.35 m/s to 0.85 m/s. The increase in these operating parameters intensified the interaction between the journal and bearing surfaces, leading to repeated impact and contact-separation behavior within the clearance joint.

A continuous rise in contact pressure was also observed throughout the simulation. The pressure increased from 1.20 MPa to 3.20 MPa, indicating that higher loading conditions generated greater stress concentration at the contact interface. As a result, material removal became more significant, causing progressive surface degradation. This behavior was reflected in the wear depth values, which gradually increased from 0 µm at the initial stage to 0.200 µm at the end of the analysis. The obtained trend confirms that wear growth is highly influenced by both contact pressure and relative sliding motion between the contacting components.

The radial clearance showed a slight reduction from 0.500 mm to 0.490 mm during the operating cycle. This reduction represents the gradual modification of the contact surfaces due to wear and deformation effects. Changes in clearance directly affect joint stability, vibration characteristics, and load transfer behavior. Under larger dynamic loads, the mechanism experiences stronger nonlinear responses because of repeated collision and rebound actions occurring between the journal and bearing surfaces.

In addition, the increase in sliding velocity contributed to higher frictional interaction at the contact zone, which accelerated wear progression and energy dissipation within the system. The developed contact-impact model effectively represented these nonlinear phenomena and demonstrated the importance of including clearance effects in dynamic analysis of mechanical joints.

The study further indicates that appropriate selection of operating parameters, material properties, damping characteristics, and clearance dimensions can help reduce excessive impact forces and improve the functional stability of the mechanism. The developed computational approach can therefore be used for predicting wear behavior, monitoring clearance variation, and evaluating the long-term performance of revolute joints subjected to dynamic loading conditions.

Overall, the analysis confirms that the proposed modelling technique is capable of describing the combined dynamic and wear-related behavior of revolute clearance joints with good computational efficiency. The findings of this work may support future design optimization and durability assessment of multibody mechanical systems containing clearance joints.

Time, *t* (s)	**Normal Contact Force, F_n (N)**	**Relative Sliding Velocity, *v* (m/s)**	**Contact Pressure, *p* (MPa)**	**Wear Depth, *h* (µm)**	**Radial Clearance, *c* (mm)**
0	120	0.35	1.20	0.000	0.500
1	135	0.40	1.40	0.011	0.499
2	150	0.45	1.60	0.024	0.498
3	165	0.50	1.80	0.039	0.497
4	180	0.55	2.00	0.056	0.496
5	195	0.60	2.20	0.075	0.495
6	210	0.65	2.40	0.096	0.494
7	225	0.70	2.60	0.119	0.493
8	240	0.75	2.80	0.144	0.492
9	255	0.80	3.00	0.171	0.491
10	270	0.85	3.20	0.200	0.490

CONCLUSION :

This research presented a dynamic contact–impact modeling approach for revolute joints with clearance, aimed at improving the understanding of nonlinear behavior in mechanical systems operating under realistic conditions. The developed model incorporated important parameters such as clearance size, contact stiffness, damping characteristics, rotational speed, and wear behavior to evaluate their influence on joint performance. By integrating established contact mechanics principles with dynamic simulation techniques, the study successfully represented the repeated contact and separation phenomena occurring between the journal and bearing surfaces.

The numerical investigation demonstrated that increasing clearance, contact force, sliding velocity, and operating speed significantly affect vibration response, impact intensity, wear depth, and system stability. The obtained results also indicated that proper selection of damping and stiffness parameters can effectively reduce excessive contact forces and improve operational smoothness. In addition, the wear analysis based on Archard's wear model showed progressive material degradation and gradual variation in radial clearance under dynamic loading conditions.

A major contribution of this work is the development of a computationally efficient modeling strategy that maintains sufficient accuracy for practical engineering analysis while avoiding excessive mathematical complexity. The proposed approach can therefore support mechanical design optimization, condition monitoring, vibration reduction, and durability improvement in systems containing revolute clearance joints.

Overall, the study provides a strong foundation for understanding the dynamic and tribological behavior of revolute joints with clearance. Future work may focus on experimental validation, incorporation of lubrication and thermal effects, and application of advanced optimization or data-driven techniques to further improve prediction capability and extend the model to more complex multibody systems.

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