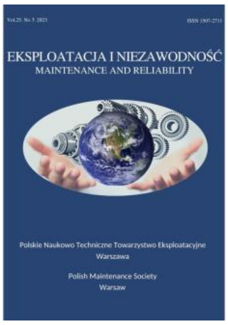

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Failure modeling and reliability analysis for motion mechanism with clearance joints under plastic deformation and wear

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Highlights

- Establishing a novel wear process model coupled with repeated impact macroscopic cumulative plastic deformation.
- Researching performance failure indicator and analysis method of motion mechanism.
- Construct an algorithm flow for wear process model coupled with repeated impact macroscopic cumulative plastic deformation.
- Operating the performance failure and reliability analysis of an engineering linkage motion mechanism.

Abstract

The performance failure and reliability of motion mechanism has a significant effect on industry reliability, operation safety and production economy. Motion precise is one of the typical performance indicators especially for motion mechanism with multibody and joints, which will be influenced by necessary joint clearance. Size of joint clearance degenerates with usage such as wear and deformation. Repeated start-stop lead to impact stress and plastic deformation for clearance joint particularly for mechanism with high load and long working cycles. Nevertheless, current research ignoring the coupling of plastic deformation and wear, which will cause a different wear process and mechanism performance failure. This study attempts to investigate the wear process and performance failure model of multibody mechanism with clearance joints considering plastic deformation and wear. Quantification of plastic deformation caused by repeated impact stress of joints is studied by formulation. Then, a novel wear process model is established on the basis of Archard model, after which performance failure indicator of motion mechanism is conducted. In case study case, a linkage motion mechanism with multi revolution joints used in industry assemble line is studied to demonstrate proposed methods and models. This investigative study provides valuable guidelines for degeneration prediction and failure or reliability analysis of motion mechanism.

Keywords
performance failure; repeated impacts; wear; mechanism reliability

1. Introduction

1.1 Motivation

Wear is one of the most common failure modes for revolute joints in multibody motion mechanism [7]. According to standard DIN 50320, wear can be defined as "the progressive loss of material from the surface of a solid body due to mechanical action, i.e., the contact and relative motion against a solid, liquid or gaseous counter body" [8]. With the development of material science and manufacturing technique, the crack failure or wear-out failure of joints appears less and less. While the changes of revolute joints clearance sizes are still unavoidable due to material loss, leading to mechanism system reliability problems or causing performance failures such as

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clamping stagnation and insufficient kinematic accuracy or motion precise. Besides, the joint axle (hinge pin) and joint sleeve (bushing) are under impact stress because of the existence of clearance, especially at the sudden start-stop or when external load changes suddenly. For multibody motion mechanism under repeated working loads, the macroscopic cumulative plastic deformation will still occur even though the stress is far less than material yield strength [11] [14] [18]. The cumulative plastic deformation would affect the wear process and wear prediction, leading to unusual motion failure for multibody mechanism. Besides, ignoring the macroscopic cumulative plastic deformation may cause catastrophic engineering failure or economic loss, especially for long-use motion mechanism.

This motivates us to build a novel model, in which the macroscopic cumulative plastic deformation caused by repeated impacts and wear process are considered coupled. Thus, the performance failure or lifetime of motion mechanism can be analyzed and predicted more accurately. The purpose of this paper is just to establish a cumulative plastic deformation coupled wear model as well as the difference of motion reliability. Besides, it has potential in reliability analysis especially for long-use motion mechanism.

1.2 literature review

The geometric dimensions and dynamic parameters of joints can be changed by wear and plastic deformation, based on which the performance failure may occur for motion mechanism. In this chapter, the literature review is carried out in two aspects, one part is about the wear process and plastic deformation analysis and their coupling, the other is about the performance failure of motion mechanism.

Wear and plastic deformation analysis

Research about joint damage or joint degeneration, including joint wear, joint plastic deformation and joint failure, always starts from the clearance dynamics and collision theory [22][24]. Wear may be the most typical mode, based on which many engineering failure cases are analyzed. For example, BAI further studied the wear damage modeling of clearance hinge and the joint failure of motion mechanism in an aerospace vehicle [2]. Haneef studied the motion principle of internal combustion engine, analyzing and predicting the wear process [10]. However, ASME Fellow, Professor Norman Jones stated that the repeated impacts may cause plastic deformation of metal parts, which is more possible to happen than the wear failure [13]. The same is true of metal revolute joints and the performance of motion mechanism may be influenced. In view of this, Professor Jones investigated the response of typical metal structures under repeated impact load, such as beam structure, plate structure, etc. Nevertheless, the calculation error increases with the increase of impact times due to the existence of material rebound effect [19]. In order to solve this problem, Truong et al. studied the response of truss structure under the repeated impact of wedge blocks, eliminated the influence of material rebound effect by modifying the initial kinetic energy, and obtained a rigid plastic theoretical solution that was in good agreement with the test [23]. Nandu studied the fracture property for gear system based on contact and energy release rate. The worn regulation and deformation of gear are both investigated [16]. Professor ZHU carried out extensive research and review on the plastic dynamic response of structures under repeated impact loads in three aspects: experimental, numerical and theoretical methods [29]. The analytical formula of rigid plasticity under repeated impact is presented [20] and used in the study of typical structures such as fixed square plate, stiffened plate and aluminum foam sandwich plate [9] [30]. Professor Flores proposed a contact model considering elastic and inelastic collision processes [7]. However, the plastic deformation factor was only introduced into the friction-wear contact modeling process, and the influence of cumulative deformation on motion transmission was not considered.

Performance failure analysis of motion mechanism

There are two kinds of failures for motion mechanism, strength failure and performance failure [26]. With the rapid development of material science and machine design level, strength failure is less and less as long as proper use. Performance failure is caused by unqualified motion target due to unavoidable degeneration such as wear or deformation. Specifically, insufficient motion precision and motion block (or clamping stagnation) are two typical failure modes for performance failures [6]. For literature about insufficient motion precision, topics are usual about error analysis, kinematic analysis and optimization. Shiakolas proposed a qualitative evaluation method for the influence of motion parameter change on the motion precise of manipulator [21]. Briot and Bonev made a detailed analysis for planar parallel robot with 3-DOF (degrees of freedom) from the point of sensor's error [3]. Karim studied the failure of a truck engine crankshaft motion system, in which failure analysis and modify methods are proposed [1]. Yin and Pan have systematically established an adaptive operation method for 6-DOF industrial robots based on their relative tracking errors under external interference and parameter uncertainty [25]. ZHAO put forward the machining strategy of mobile robot to improve its working precision by analyzing the precision of robot [28]. For literature about motion block, the research mainly revolves around failure principal analysis. IET Fellow, Professor DUAN pointed that the anti-clamping design is one of the most important part in large space-borne deployable antenna, as well as other engineering motion mechanism [5]. The factors such as machining error, assembly error and gear deformation will cause the stuck gear pair [5]. Zhao et al. pointed out that unreasonable fit clearance and uncoordinated deformation of spool and shaft sleeve caused by drastic temperature change are the main reasons for the stagnation of double nozzle flapper servo valve, and the heat-liquid-solid coupling will affect the difficulty of analysis [27].

1.3 Overview

To sum up, current studies have recognized the degeneration of revolute joint and its adverse effects on the mechanism performance. However, existing literature ignored the cumulative plastic deformation caused by repeated impact stress during the wearing modeling process, or just analyzed the response of material under repeated impact stress severally. Just as we all know, contact parameters, such as dimensional feature, friction coefficient and so on, have a great influence on wear model. Hence, ignoring the cumulative plastic deformation, which greatly influence the size or dimensional feature of contact bodies, may lead to inexact wear model. Further, the performance failure of motion mechanism cannot be predicted or estimated opportunely. It is of vital importance to do the reliability or failure analysis for motion mechanism, no matter for safety or economy. To solve the problem during failure analysis, this paper establishes a novel wear model by considering cumulative plastic deformation during wear process. The flowchart of this article is shown in figure 1.

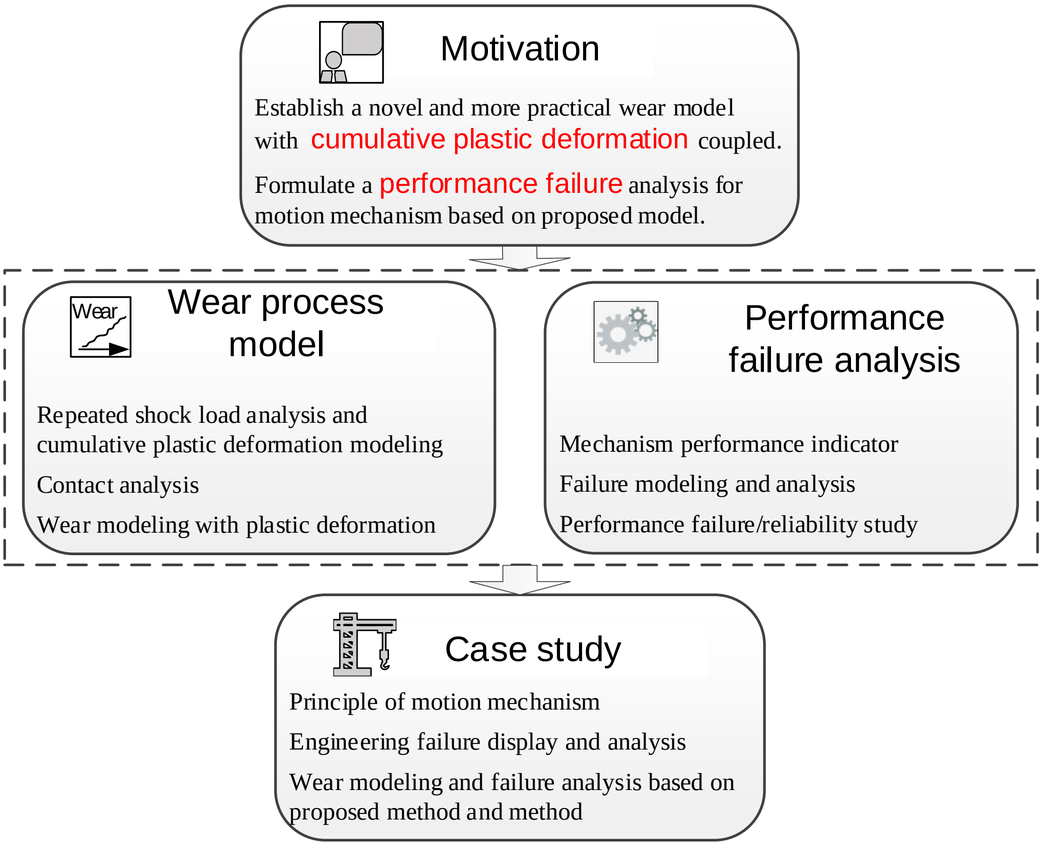


Figure 1. Article flowchart.

This study tries to make contributes at following aspects:

1) Establishing a novel wear process model coupled with repeated impact macroscopic cumulative plastic deformation.

2) Researching performance failure indicator and analysis method of motion mechanism.

3) Operating the performance failure and reliability analysis of an engineering linkage motion mechanism.

The remaining of this article is arranged as follows. Section 2 is a notations list, conventionally. Section 3 is a detail description of engineering failure and preliminary qualitative analysis. Wear modeling considering cumulative plastic deformation and performance failure analysis and studied in Section 4. Section 5 is an engineering failure case study, by which the practicability and correctness of proposed method are demonstrated.

2. System description

Systems discussed in this paper are about motion mechanisms especially linkage mechanisms with clearance. At the initial state, the positions of hinge pins and bushings are touching lightly or separated by lubricating oil just as subfigure *a* in figure 2 shows. When it starts to move or bear load, the clearance would be compressed. There will be an impact on hinge pin and bushing if it moves sharply or the load is applied suddenly. For mechanism with repeated working cycle, repeated impact stress would be generated, resulting in plastic deformation. As the actuator moves and rotate, hinge pin and bushing would wear, wearing surface may be generated just as subfigure *b* and *c* in figure 2 show. Thus, the clearance joint size changes, and the actuator may be not operated as designed, leading to performance failure.

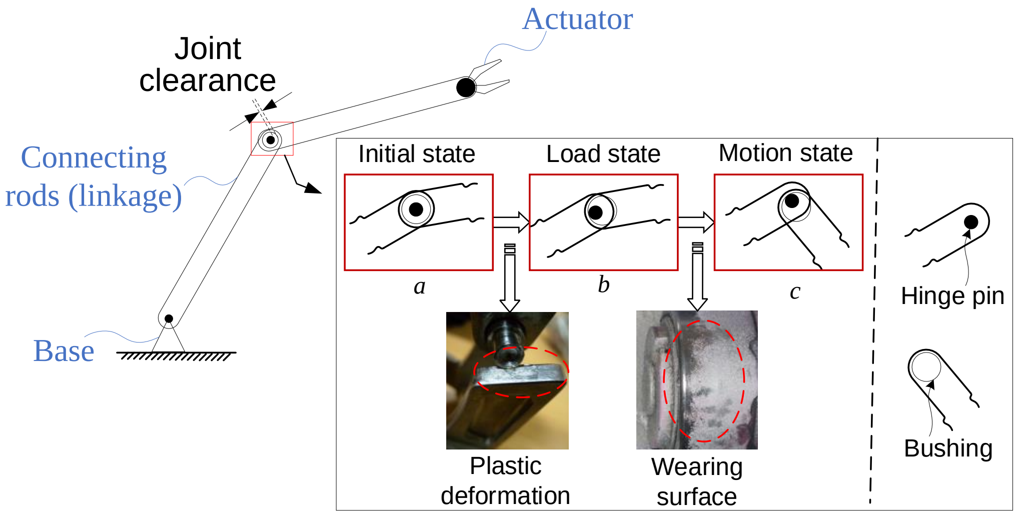


Figure 2. motion mechanism joint wear and plastic deformation.

The objective of this paper is to describe the wearing process considering plastic deformation coupled. Performance of motion mechanism is also studied. Failure or reliability analysis are conducted based on proposed methods for motion mechanism.

3. Failure modeling and analysis

3.1. Repeated impacts analysis and plastic deformation modeling

Repeated impacts on hinge pin or bushing would occur due to the clearance and sudden movement, which is usual happen in the starting stage or stopping stage of a motion mechanism. The impact load is a kind of energy load. Some of this energy is converted into kinetic energy for bouncing back, and the other is wastage. One of the reasons causing this kind of wastage is plastic deformation [17]. The microplastic deformation is related to the motion of the dislocation bend. Low temperature dislocation relaxation internal friction is produced in the process of low stress multiple impacts. Under the action of low stress and multiple impact loads, dislocation slip occurs first on grains with favorable orientation. Then, the thermal activation of multiple impact loads promoted the generation of dislocation bending and reduced the critical shear stress of dislocation slip. Under the repeated action of external stress, the bending propagated along the dislocation line, and the dislocation passed the barrier segment by segment. Finally, the entire dislocation line moved forward and the dislocation strain was generated. As the impact continues, the dislocation strain is constantly superimposed, and an unrecoverable macroscopic cumulative plastic deformation is formed.

Some assumptions are made before modeling the plastic deformation mathematically.

1) The material is continuous uniform medium;

2) Density, Poisson's ratio, elasticity modulus and other properties concerning with material stay constant before and after impact deformation;

3) Cross-sectional area of contact surface remains constant during contact process.

According to the impact stress will decay exponentially with time which can be expressed by

$$\sigma = \sigma_0 e^{-\beta t} \tag{1}$$

where, σ_0 is the initial impact stress and β is the parameter concerning with material. t is the time variable which can also be replaced by frequency f. Thus, equation (1) becomes

$$\sigma = \sigma_0 e^{-\beta/f} \tag{2}$$

The deformation magnitude is proportional to the square of the stress for microdeformation according to typical research [4]. Therefore, the plastic deformation of a single impact is described by

$$\Delta D = K\sigma^2 e^{-\alpha/f} \tag{3}$$

Due to the hardening properties, deformations of multiple impacts are not constant. The deformation of a single impact decreases with the increasing of impacts numbers because of strain-hardening. In this paper, we supposing that the deformation caused by a single impact is fixed ratio to deformation caused by the last impact. Specifically,

$$\Delta D_N = \Delta D_{N-1} q \tag{4}$$

where N is the number of impacts and ΔD_N is the deformation caused by N_{th} impacts. q is the fixed ratio or deformation attenuation coefficient.

Consequently, the cumulative deformation after N impacts is expressed by

$$D = \sum_{i=1}^{N} \Delta D_i = K\sigma^2 e^{-\alpha/f} \frac{1-q^N}{1-q}, \quad i = 1,2,3 \tag{5}$$

The cumulative deformation would influence the size of joint clearance, causing the changes of dynamic of joint. As a consequence, there would be a different wearing process which we would study at the next section in detail.

3.2. Wear analysis considering joint plastic deformation

Archard wear model is the most typical method to analyze wear process, whose validity and practicability are demonstrated definitely [7] [15]. It is used to model the wear process and as a basis to develop the modified method in this paper. Some assumptions are necessary here as following:

(1) Assuming that there is no fatigue crack for joints during wear process. Only progressive loss of material from the surface is considered.

(2) Ignoring the lubricant and the pressure caused by lubricating oil.

(3) Assuming there is no chemical reaction in wearing process, which may lead to shifting mechanical propertied of joints.

The mathematic express of Archard model is

$$\frac{V}{s} = \frac{kF_n}{H} \tag{6}$$

where V and s are worn volume and sliding distance respectively. F_n is the normal contact force and H is the material hardness with a non-dimensional wear coefficient k. Divide both sides of this equation by contact area, then equation (7) would be obtained.

$$\frac{h}{s} = \frac{kp}{H} \tag{7}$$

where h is the worn depth and p is the contact stress. Worn depth has a great advantage comparing with volume in mearing especially for the hinge pins and bushings of revolute joints. Besides, it is also convenient to re-built the worn radius and outlines by worn depth instead of volume.

The key point to solve Archard model is to get an accurate contact stress which could be analyzed by Hertz contact model [12]. Due to the existence of initial plastic deformation caused by shocks or impacts, the Herts model is modified in this section. According to Hertz contact theory, the contact between hinge pin and bushing of clearance joint is simulated to contact of plane stress in an infinite-length plate with width $2a$. It is known that the center contact surface has the maximum stress denoted by p_0, then the stress distribution along width is expressed by

$$p(x) = p_0 \left(1 - \frac{x^2}{a^2}\right)^{\frac{1}{2}} \tag{8}$$

x is the distance along width between contact point and center. Further, the maximum contact stress is conducted according to Hertz theory as equation (9) shows.

$$p_0 = \sqrt{\frac{F(R_2 - R_1)}{\pi R_2 R_1 \left(\frac{1-\upsilon_1{}^2}{E_1} + \frac{1-\upsilon_2{}^2}{E_2}\right)}} \tag{9}$$

in which R, E and υ are radius, elasticity modulus and Poisson's ratio of hinge pin or bushing. Corner mark 1 is for hinge pin and 2 is for bushing. Subfigure *a* of figure 3 shows the geometric relationship of the contact process. O_2 and O_1 are the circle centers of hinge pin and bushing. C is the clearance size of the joint, or rather, the distance of O_1 and O_2. If plastic deformation caused by impacts or shocks ignored, the wear process would make a worn surface as subfigure *c* shows. However, just as what we said above, the plastic deformation would be generated due to impact. These impacts are always occurred in the starting or stopping moment of motion mechanism, as the clearances of joints are compressed suddenly, especially for mechanism with as heavy load. Therefore, the contact state changes just as subfigure *b* shows. In detail, the actual radius of hinge pin and bushing are different from them in subfigure, and then wear process leads to a worn surface in a different way as subfigure *d* demonstrates.

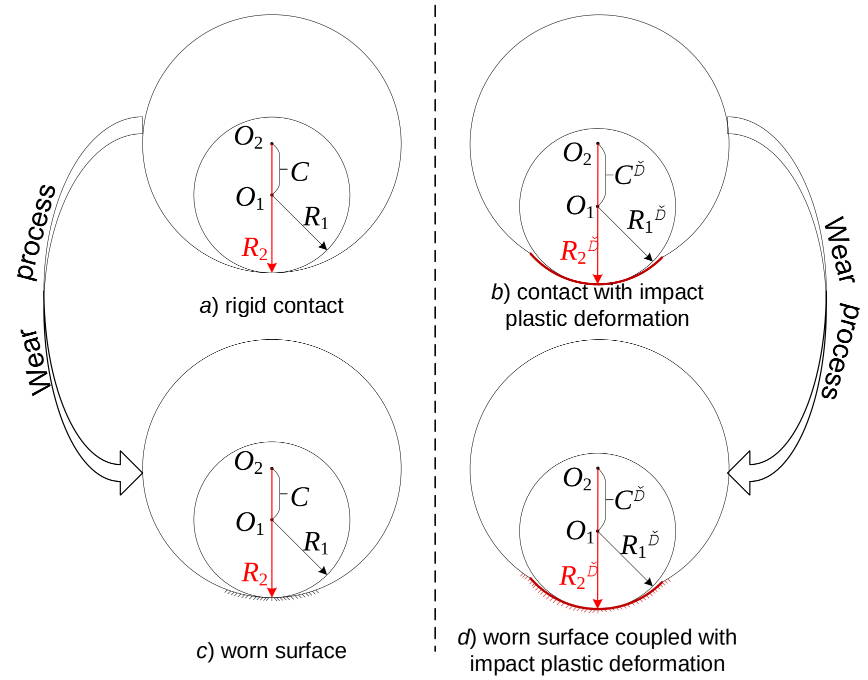


Figure 3. wear diagram considering impact plastic deformation.

According to equation (5) and figure 3, the effective radius is expressed by

$$R' = R - D$$

$$= R - K\sigma^2 e^{-a/f\,\frac{1-q^N}{1-q}} \tag{10}$$

Thus, the maximum contact stress for wear analysis is conducted as

$$p_0 = \sqrt{\frac{F(R_2{}' - R_1{}')}{\pi R_2{}' R_1{}' \left(\frac{1-\upsilon_1{}'}{E_1} + \frac{1-\upsilon_2{}'}{E_2}\right)}}$$

$$= \sqrt{\frac{F\left(R_1 - K_1\sigma^2 e^{-\frac{a_1}{f}\frac{1-q_1{}^N}{1-q_1}}\right) - \left(\left(R_2 - K_2\sigma^2 e^{-a_2/f\frac{1-q_2{}^N}{1-q_2}}\right)\right)}{\pi\left(R_1 - K_1\sigma^2 e^{-\frac{a_1}{f}\frac{1-q_1{}^N}{1-q_1}}\right)\times\left(R_2 - K_2\sigma^2 e^{-\frac{a_2}{f}\frac{1-q_2{}^N}{1-q_2}}\right)\times\left(\frac{1-\upsilon_1{}'}{E_1} + \frac{1-\upsilon_2{}'}{E_2}\right)}} \tag{11}$$

based on which wear depth can be calculated. With the movement of mechanism and rotation of joint, the contact force and contact position are changing with time. As a consequence, equation cannot be used directly while a differential form should be appropriate. The differential form is expressed by

$$\frac{dh}{ds} = \frac{kp}{H} \tag{12}$$

$$h = \int \frac{kp}{H} ds$$

$$= \int \frac{kp}{H} \omega r dt \tag{13}$$

dh, ds are the unit value of wear depth, sliding distance in a discrete unit time interval dt. ω and r are the rotation angle velocity and efficient radius.

3.3. Motion performance failure analysis

Insufficient motion precision and motion block (or clamping stagnation) are two typical failure modes for performance failures [26]. The performance failure is demonstrated according to its ideal value and actual value. A typical mathematical expression of performance failure is just as equation shows.

$$|\theta_a - \theta_0| > \delta \tag{14}$$

where θ_a is the actual value of performance indicator and θ_0 is its ideal value. δ is the threshold of the indicator error. Due to the actual value of performance indicator θ_a is a function of several parameters such as parts dimension or time, it can also be written as:

$$\theta_a = f(t, \vec{L}, \vec{F}, \vec{E}) \tag{15}$$

where t, $\vec{L}$, $\vec{F}$,$\vec{E}$ are time, geometric dimensions of the parts, load and force, environmental factors, specifically Typical performance indicators include motion position, moving angle, motion resistance and so on. Thus, equation (14) can be deduced as

$$|\theta_a - \theta_0| < \delta \tag{16}$$

Consequently, failure probability is expressed by

$$F_{sys}(t) = P\{|\theta_a - \theta_0| < \delta\} \tag{17}$$

For the calculation of performance failure probability, performance indicator θ_a and its error threshold δ are determined according to its actual operation. Then, the math expression (15) is deduced. If the relationships among indicator and its parameters is clear, an explicit expression is useful. However, some mathematical methods are helpful such as surrogate model, approximate expression or neural network model for implicit expression. For the situation that parameters are random or uncertain, the failure probability or reliability probability can be obtained according to equation (15) and equation (17) by mathematical statistics, MC (Monte Carlo) method, experimental programming method and so on.

3.4. Algorithm simulation procedure

Totally, the algorithm procedure of proposed method is summarized below with a simulation flow chart in figure 4.

Step 1: Analyze the principle of motion mechanism through typical methods or computer simulation, and extract dynamic properties of clearance joints including contact stress, contact position angle and so on.

Step 2: Obtain the repeated impacts regulation based on step 1. Simulate the contact stress and cumulative plastic deformation D according to equation (2) to (5).

Step 3: Start to simulate the repeated impacts deformation coupled wearing process. Calculate the advanced clearance size R' on the basis of step 2 and equation (10), which is an important input of wear analysis.

Step 4: With the advanced clearance size R', conduct coupled wear process expression and calculate the wear volume or wear depth according to equation (6) to (13).

Step 5: Establish the performance indicator of motion mechanism and its expression according to equation (15).

Step 6: Repeat step 3, step 4 and step 5 for n times until n reaches the pre-setting work cycle N or the performance failure indicator reaches its threshold.

Step 7: Get the analysis result such as failure probability, performance lifetime of motion mechanism.

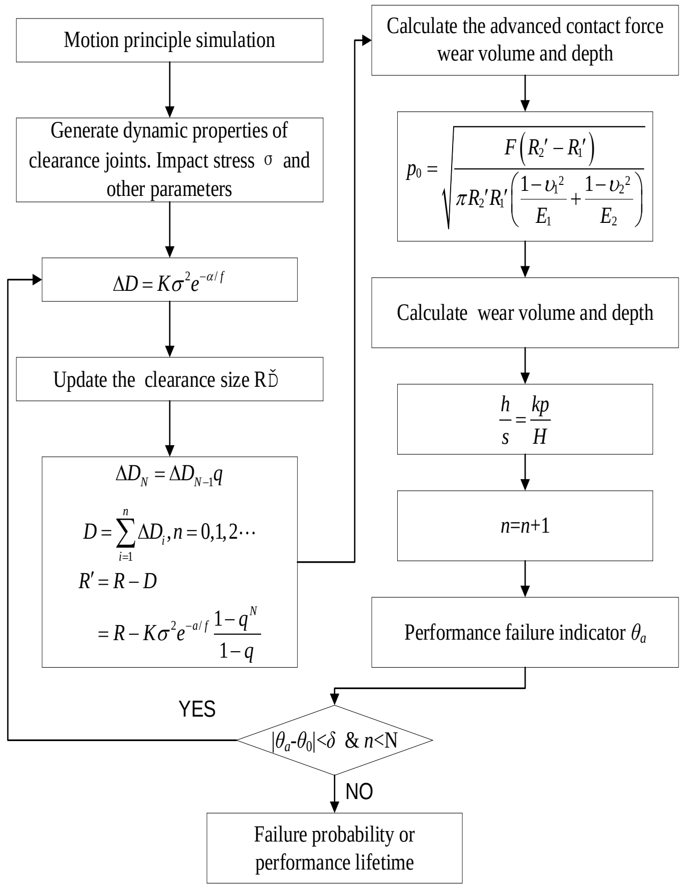
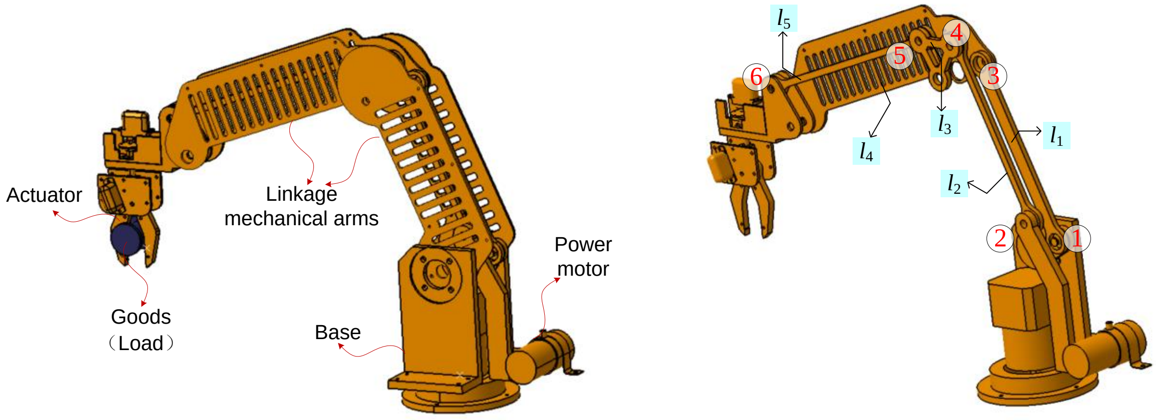


Figure 4. Simulation flow chart.

4. Case study

In this section, a linkage motion mechanism with multi revolute joints used in industry assemble line is studied. The structure of this mechanism is shown in subfigure *a*, figure 5, which is composed by actuator, linkage, power motor and base. Power motor is the power producer, driving the actuator to move as designed through the linkage mechanism arms and carrying load from its origin to its specific destination position. The mission of this mechanism is to carrying goods over and over again. A working cycle is defined as that actuator carries goods from initial position to destination position.



a. compose diagram *b*. key-part view

Figure 5. structure of a linkage motion mechanism.

The motion precise of actuator has a great relationship with the linkage mechanical arms and its joints. Exploded view of linkage mechanical arms is shown in subfigure *b*, figure 5, with 6 joints and 5 rods numbered. The repeated mission would give rise to wear and repeated impacts, lead to generating clearances' sizes. Critically, goods cannot be carried to its designed position anymore. Economic loss even catastrophic accident may occur. Thus, it is of vital importance to analyze the changing law of these 6 joints and the motion precise of this mechanism. If the joint is perfect, the constrain force of each joint is shown in figure 6. From this picture we know that the motion mechanism starts to operate at initial time and it carries load at 2s until 3s, then return to its initial position at 5s. However, due to the existence of joint clearance, there will be an impact force at the moment that load is dropped off, just as shown in figure 7. It is the impacts that cause, the plastic deformation of joint, leading to unexpected clearance size changing. For simplicity without loss of generality, we just consider the plastic deformation and wear of the bushing, regardless them of joint pin. Necessary notations are listed in table 1.

Table 1. Parameter values and sources.

Notation	Meaning	Value	Source
K	Constant parameter of material	5.953×10^{-8}	Reference [11]
α	Constant parameter of material	0.36117	
q	Impact deformation constant	0.99969	
f	Frequency of impacts	0.2	
k	Wear coefficient	1.734×10^{-4}	Reference [2]
H	Material hardness	2.17×10^{9}	
E	elasticity modulus	206GPa for hinge pin 1.39Gpa for bushing	
R	Initial radius	15mm for hinge pin 15.3mm for bushing	Design data
υ	Poisson's ratio	0.29	
l_1	Length of rod l_1	331mm	
l_2	Length of rod l_2	305mm	
l_3	Length of rod l_3	244mm	
l_4	Length of rod l_4	559mm	
l_5	Length of rod l_5	476mm	
δ	Threshold of the performance error	0.01mm	

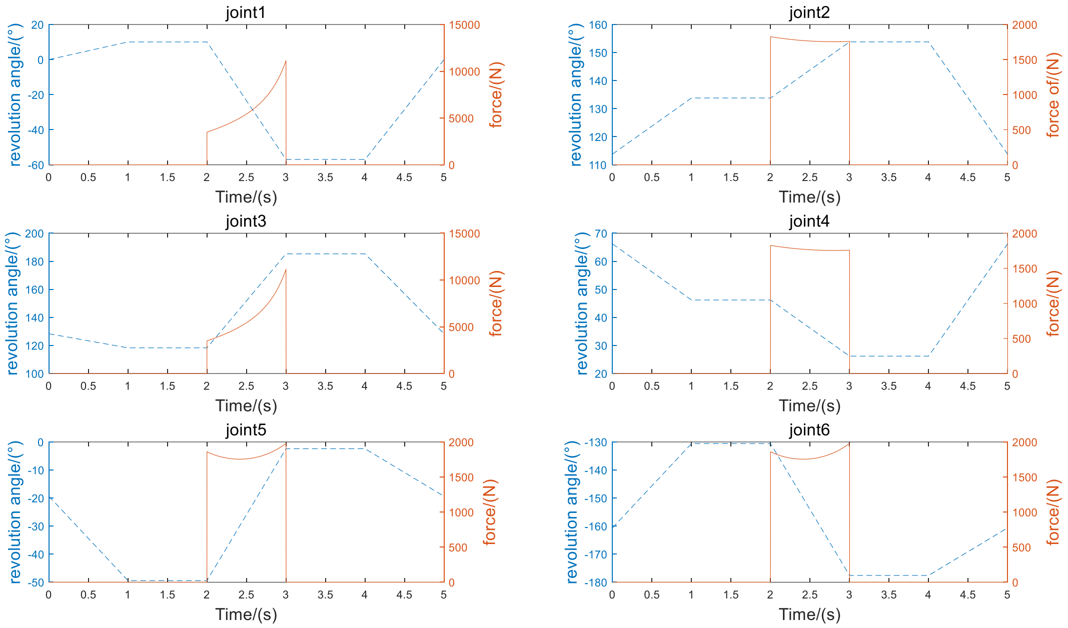


Figure 6. constrain force of each joint (ideal situation).

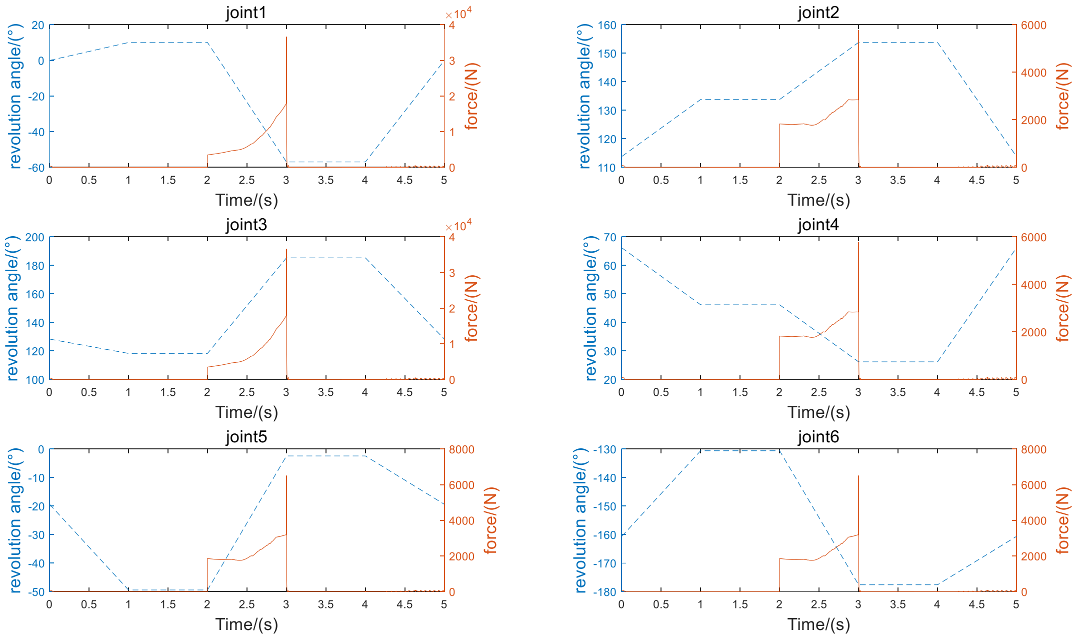
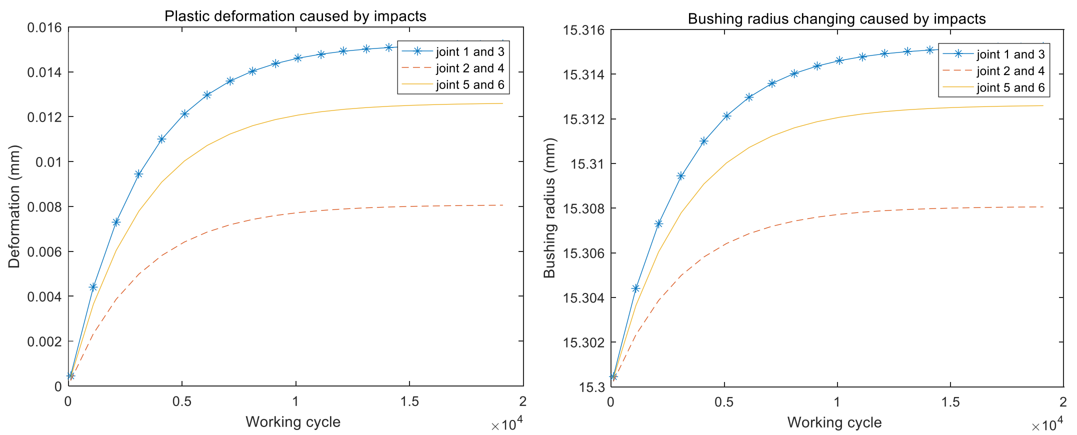


Figure 7. constrain force of each joint (situation considering clearance).



a deformation size *b* bushing radius size

Figure 8. sizes change due to deformation.

Due to the repeated impacts, plastic deformation is calculated according to equation (1) to (5). The deformation sizes change with mission cycle which is shown in figure 8. From figure 8 we know that due to plastic deformation caused by repeated impacts, the bushing radius sizes increase. However, when mission cycle reaching about 15000, the size change becomes inapparent due to the hardness. Although plastic deformation may not increase obviously, it still has an influence on wearing process, which will be demonstrated later.

According to above analysis and equation (9) to (13), the wear process of these joints are calculated. Because of the differences of plastic deformation and load, the wear depth and angle vary with joints. Figure 9 is the error circle outlines of different joints at various mission circles. With the usage and operating of motion mechanism, the error circle becomes irregular. The worn and plastic deformation positions of different joints varies because the differences of contact angle and mechanism forces.

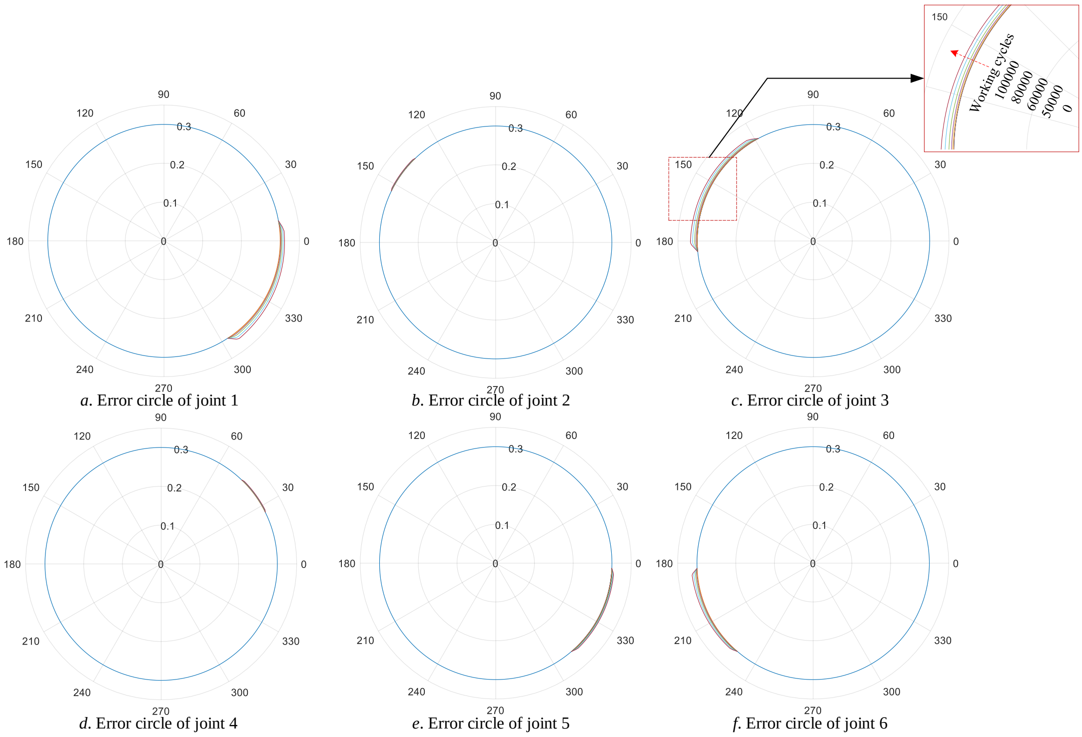


Figure 9. error circles of joints.

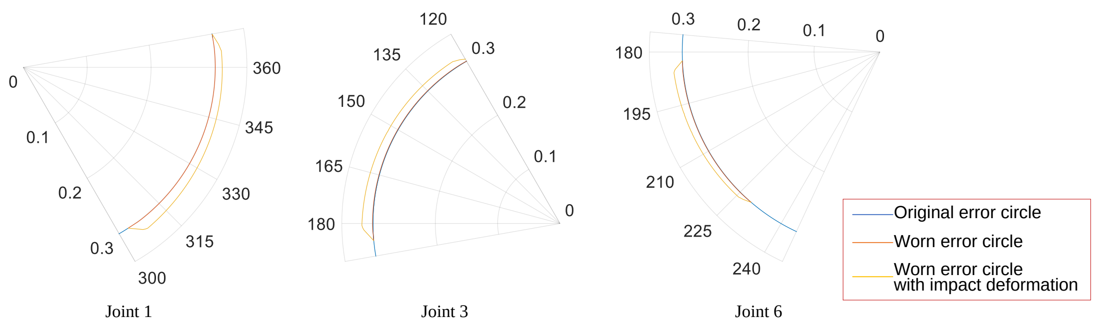


Figure 10. error circles of origin, worn state and worn state with impact deformation.

Wear depth of joint 1, 3 and 6 is the most, which is used to demonstrate the difference between wear considering impact deformation and wear regardless impact deformation. Figure 10 manifests the differences among error circles of origin, worn state and worn state with impact deformation at 100000 working cycles. From figure 10 we know that wearing process considering deformation has a more obvious effect on error circle radius.

Wearing process considering impact plastic deformation has a great influence not only in joint clearance size, but also in mechanical performance especially. Just as discussed in introduction section, the failure of a part is rare while the degradation performance is obvious. This case is composed by several connecting rods, which is easier to accumulate the error and lead to performance failure. Figure 11 shows the working cycle of this mechanism, carrying goods from initial position to destination position as precise as possible. The performance failure is demonstrated by both X and Y coordinate value.

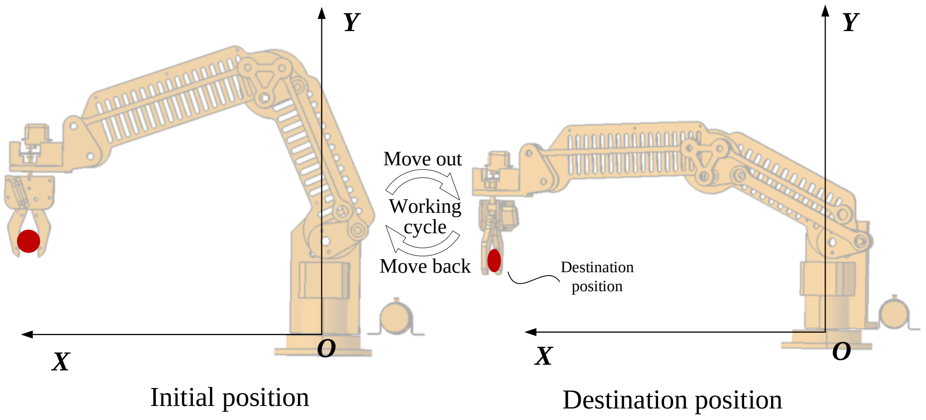


Figure 11. working cycle of mechanism.

By dynamic data of this model, the position distance expression of this case mechanism is

$$d = 162.49 - 0.00688l_1 - 0.00951l_2 - 0.0399l_3 - 0.00834l_4 - 0.142l_5$$

where d is the actual position of goods. If distance between the actual position and perfect position exceed threshold, performance failure occurs. According to equation (17), the failure probability can be calculated by MC method. Figure 12 is the diagram of performance failure probability, from which the proposed method is more accurate than wear model regardless plastic deformation comparing with simulation result. It demonstrates the valid of proposed model. Besides, the performance failure rate of proposed model has larger values and larger increasing rate, which confirm the deduction that plastic deformation caused by repeated impacts influences the wear process, accelerating the wear progress. In other words, it would make a paranormal reliability result and cause unexpected failures to ignore the plastic deformation in wearing process and motion failure analyses.

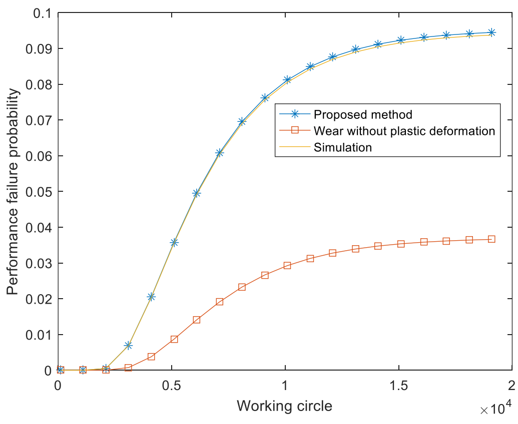


Figure 12. Performance failure probability of motion mechanism.

Figure 13 illustrates the sensitive analysis of performance threshold δ. It is easy to understand that the larger the threshold value, the smaller the performance failure probability. Besides, the difference values among various threshold increase with working cycles, which indicates that the influence caused by repeated impacts deformation enlarged by usage.

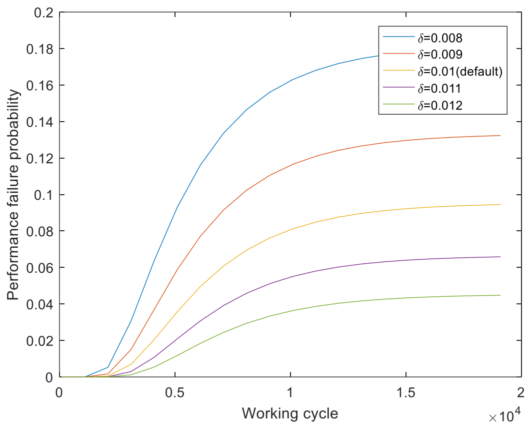


Figure 13. Sensitive analysis of threshold δ.

5. Conclusion and discussion

A novel wear model considering repeated impact plastic deformation is researched in this study, as well as the performance failure of motion mechanism. An engineering motion mechanism is selected as a case to demonstrate the valid of proposed model and method.

1. Repeated impacts is caused by the necessary joint clearance and sudden load or movement of mechanism, which leads to cumulative plastic deformation of joints. Wear process is also affected by it. A modification wear model is proposed

considering cumulative plastic deformation on the basis of Archard model and the mathematical expression is conducted in this study.

2. Performance failure indicator and its expression of motion mechanism is given, based on which mechanism system failure probability or reliability can be analyzed.

3. Form case section, wearing processes with and without repeated impact plastic deformation are compared, which demonstrate the viewpoint that wearing process is changed.

4. From case section, wearing depth calculated by proposed method is more accurate than it without plastic deformation comparing with simulation results, which demonstrates the valid of proposed method.

There are also some shortcomings in this study which can be improved in future research such as the changing property of joint material after impacts, considering different lubrication condition.

Notations

Table 2. Notation list.

Notation	Meaning
K	Constant parameter of material for repeated impact plastic deformation
α	Constant parameter of material for repeated impact plastic deformation
β	Constant parameter of material for repeated impact plastic deformation
q	Impact deformation constant
f	Frequency of impacts
D	Cumulative plastic deformation
σ	Impact stress
σ_0	Maximum impact stress
ΔD	Plastic deformation caused by a single impact
V	Worn volume
h	Worn depth
Fn	Normal contact force
s	Sliding distance
k	Wear coefficient
H	Material hardness
p	Contact stress of wearing process
p_0	maximum stress of contact surface
R	Initial radius of hinge pin or bushing
E	elasticity modulus
υ	Poisson's ratio
l_i	Length of rod l_i
O	Center of pin or bushing
C	Clearance of joint

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