Nonlinear Dynamics Analysis Based on Node Model of Contact Surface

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Abstract. The friction motion exists generally in the mechanical operation structure. The target of the paper is to predict and optimize the dynamic performance of the mechanical structure via the structure design. The kinetic equation of discrete-node model is established based on the theory of the characteristic parameters of the interface node model. The nonlinear dynamic equivalent analysis method of the node model is constructed. The method is applied to analyse the nonlinear dynamic characteristics of the operating mechanism of the micro-circuit breaker, to find the relationship between the external driving force and the interface of the force on the mechanical parts, and then the design method is constructed. The method is more accurate to predict the motion characteristic of the mechanical structure.

Introduction

The mechanism is formed by the combination of the components according to the requirement, the surface between the parts and the components in the mutual movement is the mechanical surface, and short name is contact surface. In order to display the relationship of the contact surfaces and the load, deformation respond and the dissipation of the energy, the microscopic contact theory of the interface is studied specially.

Based on the research of the unit sample, OSTROVSKII [1] test the performance of classic interface acquired and induced, to obtain that the deformation of the contact surface caused by the normal pressure of the contact is the nonlinear function, and approximatively form the exponential function via fitting. BURDEKIN [2] studies the influence of the performance of tangential force on the contact surface to reach the nonlinear relationship of the tangential contact stiffness and pressure on the contact surface, and increase with the more deformation of the contact surface. Meiyu Huang [3] etc. acquired a larger number of contact parameters by the experimental method, and presented the dynamic characteristic parameters of contact surface by structural modeling method of artificial neural network. It shows that the essence of damping mechanism of lag deformation of the fixed contact surface is the damping energy dissipation mechanism of the fixed contact surface, in which the micro slip damping energy dissipation in the contact surface is main, and supplemented by the micro local impact damping. Guanhua Dong[4] etc. considering the coupling relation-ship between the substructure, to Manipulative offset the unpredictable frequency response matrix to be supposed as an intermediate variable, avoiding the introduction of error equation when using the unpredictable frequency response structure and estimating structural frequency response matrix. Ling Li[5] etc. constructed a new polynomial function to describe the relationship between the contact deformation and the contact area, according to that the real contact surface of the micro convex and the transformation of contact load in the critical point of transformation of the deformation condition meet the continuity and smoothness condition.

In order to solve the problem of discontinuity in elastic deformation area, the node model is established in the actual situation, to construct new nonlinear dynamic characteristic polynomial function. The relationship among micro-contact surface /the contact load /the deformation response and the energy dissipation is established, to verify the feasibility of the micro contact analysis method in the elastic deformation zone via analysing the nonlinear dynamic characteristic of the operating mechanism of the micro-miniature circuit breaker.

Node Modelling Theory on the Contact Surface

The contact behave exhibits the elastic deformation mainly in the transient motion. In the elastic region, the contact behave of the single micro convex can be described by the Hertz contact theory. In order to study the contact deformation mechanism of the transient, the contact transient process of the micro convex is regarded as the contact process of the node. The deformation mechanism of the contact model of the node is in the Fig.1 as following:

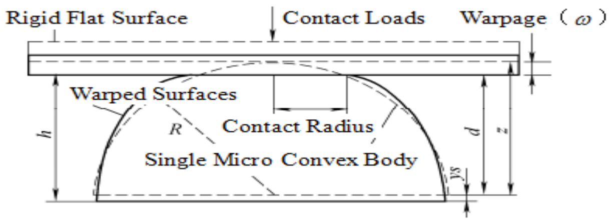


Figure 1. The relation of contact loads and contact surface

Deformation Mechanism of the Node Model Elastic Contact

The node model can be made an analogy with the contact model of the micro convex, in which the slipping and rolling are the main forms of the motion, the transient contact surface can be regarded as the contact motion of a micro convex ball with a provided plane. From the Fig. 1, it is concluded that the relationship of the maximum deformation ω in the elastic region, contact surface δ_e and the contact load f_e.

$$\delta_e = l \times 2R\cos\frac{\sqrt{R^2-\omega^2}}{R} \tag{1}$$

$$\delta_e = \pi R\omega \times \frac{l}{\sqrt{R^2-\omega^2}} \tag{2}$$

$$f_e = \frac{4}{3}ER^{\frac{1}{2}}\omega^{\frac{3}{2}} \times \frac{l}{\sqrt{R^2-\omega^2}} \tag{3}$$

In the formula, E -the composite elastic modulus of the contact materials.

$$\frac{1}{E} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{4}$$

E_1, E_2 - Elastic modulus of the contact materials.

ν_1, ν_2 -Poisson ratio of the contact materials.

R -Radius of equivalent curvature of the top of the micro convex body.

Research on Equivalent–Method of Node Model

The dynamic performance of the contact surface effects the motion behavior of the mechanical system. Due to the characteristics of the contact surface are influenced by many factors, the nonlinear coupling relationship of the complex contact surface is difficult to be described by the pure theory. Take the specific micro-surface of the contact surface for example, it is difficult to apply the experimental characteristic parameters to the practice caused by the diversification, nonlinear, multi-coupling of the contact force.

Provided that the two contact bodies possess the same structure and material in the mechanical operation system, and the transient contact surface can be regarded as the contact of two rigid smooth plane after deformation. Based on the hypothesis of contact condition.

(1) The micro-topography on the surface of two contacts in the operation structure is isotropic.

(2) The node model in the contact surface shows the elastic deformation in transient motion, and continuously deform between two transient motions and the amount of deformation are not effected each other.

(3) The top of all the convex node models in transient state is sphere, and the radius of the curvature is the same.

(4) Convex node model just take place the elastic deformation when contact, possess the non-deformation performance of the macro-matrix of the contact body of the motion-rail.

In the transient contact, N micro convex bodies have appeared on the surface of the two contact, the amount of micro convex bodies on the node model is antiquated as:

$$n = N\int_d^\infty \lambda_x f(z)dz = \eta S_n \lambda_x \int_d^\infty f(z)dz \tag{5}$$

In the formula, η is the distribution density of the amount of the micro convex bodies.

$f(z)$-The probability density function of the height distribution of the micro convex bodies.

λ_x -The inertia weight of the deformable body in the joint model.

d - The average distance of the surfaces of two convex bodies.

The elastic deformation of the contact surface is highly subject to the normal distribution, therefore the height distribution $f(z)$ of the micro convex body is assumed to be:

$$f(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(z-\theta)^2}{2\sigma^2}\right) \tag{6}$$

In the formula, θ is the average height of the contact surface.

z -The height of the micro convex bodies.

$z = d + \omega$

σ -The standard deviation of the height distribution of contact area.

When the micro convex bodies contact in the node model, the real contact form in the contact surface is the plastic deformation, the contact area is the sum of all the micro convex bodies, namely:

$$A_T = A_e = \eta S_n \lambda_x \int_d^{d+\omega_e} a_e f(z)dz \tag{7}$$

In the formula,

A_e -The real contact area of elastic region on the node model contact surface.

A_T -The real contact area of the node model contact surface.

In the same way, the total contact load on the surface is:

$$F_T = F_e = \eta S_n \lambda_x \int_d^{d+\omega_e} \gamma_e f(z)dz \tag{8}$$

In the formula:

F_e -The real contact load of the surface of the node model in elastic region.

F_T -The real contact load of the surface of the node model.

The contact rigidity is the important part of the integral rigidity of the mechanical structure, sometimes even the weak link in the overall stiffness. The stiffness characteristic of the micro convex body contact of the node model is equivalent to the linear spring, namely the single micro body contact, the contact stiffness of the elastic stage is k_e respectively, according to the contact rigidity of single micro convex contact, the following formula can be concluded:

$$k_e = \frac{df_e}{d\omega} = \frac{2}{3} E R^{1/2} l \sqrt{\frac{(R^2-\omega^2)^2}{3\omega^2 R^2 - \omega^4}} \qquad \omega < \omega_e \tag{9}$$

The contact stiffness K_T of the node model contact surface is:

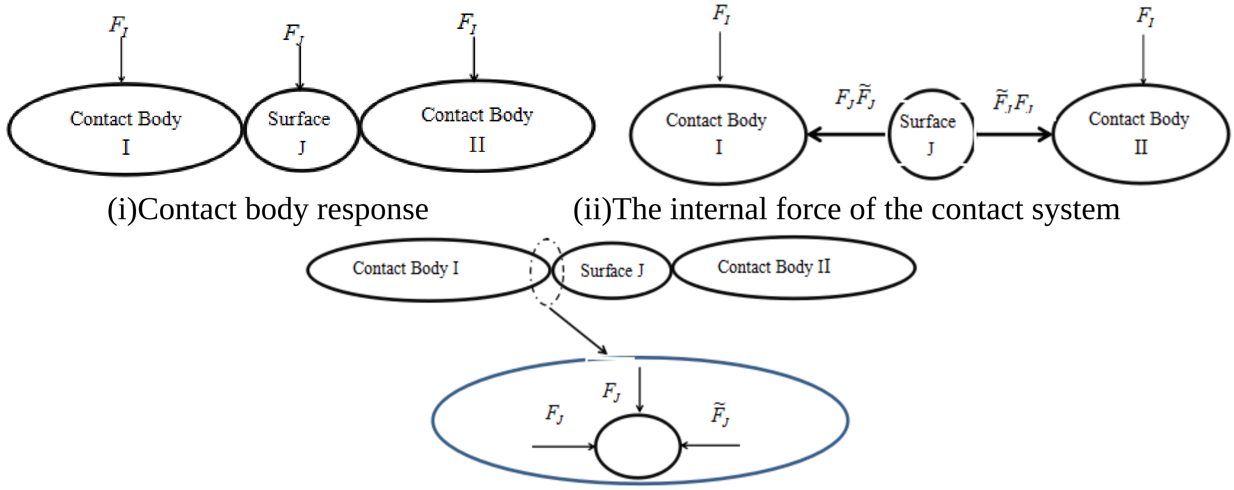
$$K_T = K_e = \eta S_n \lambda_x \int_d^{d+\omega_e} k_e f(z)dz \tag{10}$$

Motion Mechanism of the Node Model

The core problem of contact surface of the node model is the friction of two contact bodies. The friction occurs in two forms in the dynamic function: force in the first analysis method and moment in the second analysis method. The research on the contact model on the surface of friction possess an important practice value, the surface have remarkable influence on the movement characteristic of the micro-operation structure. For the micro-structure, the operation force is nonlinear feedback from the consumption of input energy on the friction on the contact surface.

The friction and moment are introduced into the research of structure and the machinery system dynamics of the node model on the contact surface, the calculation will be nonlinear, which will bring difficulties to the dynamic analysis and calculation of the operating mechanism. The establishment of the friction model of contact surface is the key to the analysis of the mechanical system from the parts to the whole operation.

It is available to regarded the node model system as a contact dynamic system which is composed of two moving continuously contact bodies, and the system can be split and return to the independent joint model in the transient state.



(i)Contact body response (ii)The internal force of the contact system

(iii)Force analysis of the node model

Figure 2. Dynamics analysis of the contact body

The response relationship of the contact structure is:

$$\begin{Bmatrix} X_I^1 \\ X_J^1 \\ X_J^2 \\ X_I^2 \end{Bmatrix} = \begin{bmatrix} H_{II}^{11} & H_{IJ}^{11} & H_{IJ}^{12} & H_{II}^{12} \\ H_{JI}^{11} & H_{JJ}^{11} & H_{JJ}^{12} & H_{JI}^{12} \\ H_{JI}^{21} & H_{JJ}^{21} & H_{JJ}^{22} & H_{JI}^{22} \\ H_{II}^{21} & H_{IJ}^{21} & H_{IJ}^{22} & H_{II}^{22} \end{bmatrix} \begin{Bmatrix} F_I^1 \\ \overline{F}_J^1 \\ \overline{F}_J^2 \\ F_I^2 \end{Bmatrix} \tag{11}$$

The response relationship of the contact bodies and the contact surfaces:

$$\begin{Bmatrix} X_I^1 \\ X_J^1 \\ X_J^2 \\ X_I^2 \end{Bmatrix} = \begin{bmatrix} H_{II}^{1} & H_{IJ}^{1} & 0 & 0 \\ H_{JI}^{1} & H_{JJ}^{1} & 0 & 0 \\ 0 & 0 & H_{JJ}^{2} & H_{JI}^{2} \\ 0 & 0 & H_{IJ}^{2} & H_{II}^{2} \end{bmatrix} \begin{Bmatrix} F_I^1 \\ F_J^1 \\ F_J^2 \\ F_I^2 \end{Bmatrix} \tag{12}$$

The dynamic characteristic of the node model:

$$\begin{Bmatrix} \tilde{F}_J^1 \\ \tilde{F}_J^2 \end{Bmatrix} = M \begin{Bmatrix} X_J^1 \\ X_J^2 \end{Bmatrix}$$

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

$$M = K_T + \lambda C \tag{13}$$

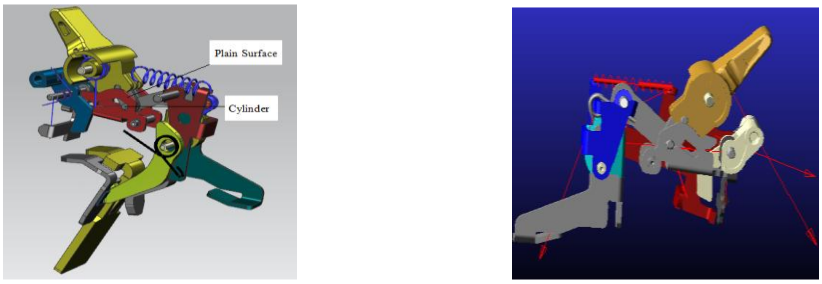
From the mechanical equilibrium, it can be concluded:

$$\begin{Bmatrix} F_J^1 \\ F_J^2 \end{Bmatrix} + \begin{Bmatrix} \tilde{F}_J^1 \\ \tilde{F}_J^2 \end{Bmatrix} = \begin{Bmatrix} \bar{F}_J^1 \\ \bar{F}_J^2 \end{Bmatrix} \tag{14}$$

In the formula, $\tilde{F}_J$ is the force of the contact body on the contact system. F_J is the force of the node model on the contact system. $\bar{F}_J$ is the force of node in the node model.

The Application on the Close Operation of Miniature Circuit Breaker

Node model analysis method was applied to miniature circuit breaker (short for WCB) operating mechanism. The closing process of the WCB need to overcome a variety of resistances, such as reset spring resistance, contact resistance and electromagnetic resistance etc..The most complex and uncertain resistance is the resistance of the contact surface, which using the Node model analysis method. As shown in the Fig 3, contact bodies are the rigidity curve groove contact surface which show v-shaped and cylindrical surface respectively, and the material of the contact bodies is the same. To design the node modeling, and to calculate the velocity and acceleration of body contact, and the change of the contact resistance.



(i)Node modeling (ii)The closing process

Figure 3. Modeling and Simulation

Cylindrical contact surface along the v-shaped groove in the movement. Under the action of a driving force in the operating mechanism, the output force of the cylinder axis is 6.3 newton, and the input Force is19.8 newton, when the driving force is 3.6 newton. To overcome the contact surface resistance is 13.5 newton roughly.

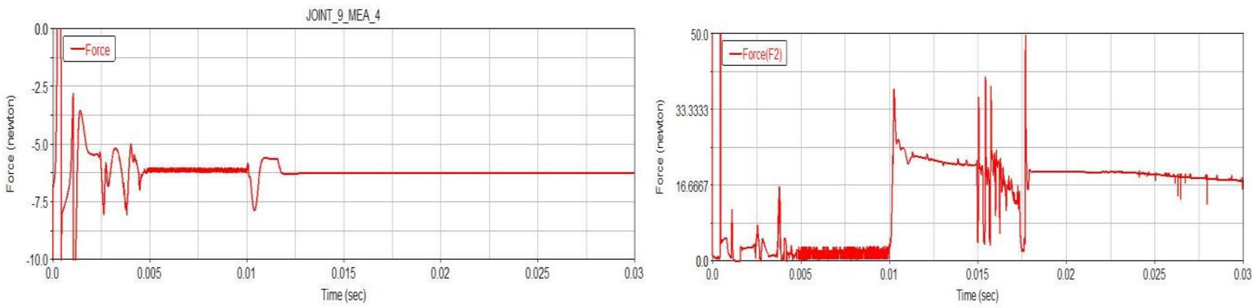


Figure 4. The contact force analysis under 3.6 newton

Under the action of a driving force in the operating mechanism, the output force of the cylinder axis is 19.6 newton, and the input Force is26.5 newton, when the driving force is 3.6 newton. To overcome the contact surface resistance is 6.9 newton roughly.

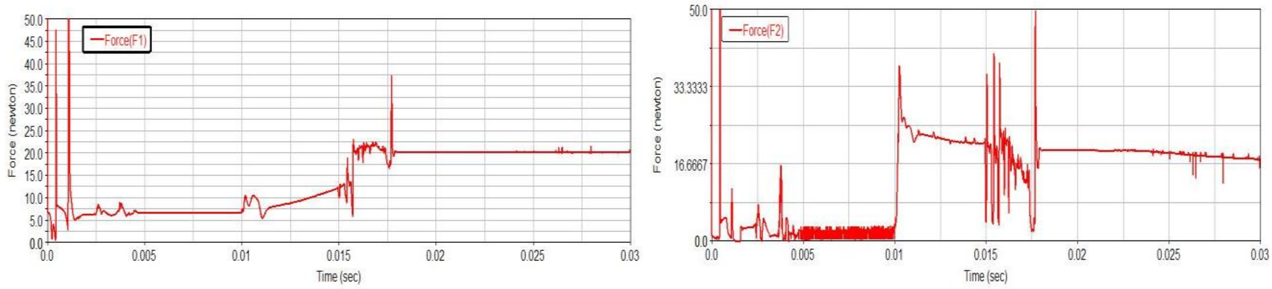


Figure 5. The contact force analysis under 10 newton

Conclusion

(1) This paper put forward a method improved on the analysis between the Contact stiffness and contact load by the node model.

(2) The contact stiffness increased with the increase of elastic deformation of real contact load. Contact stiffness and contact area tend to ideals contact stiffness and ideals contact area when the contact load increases to a certain extent.

(3) The contact stiffness increase fast in the initial contact. It is the nonlinear dynamic relationship between contact stiffness and contact load.

Acknowledgments

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References

1. GREENWOOD J A, WILLIAMSON J B P. Contact of nominally flat surfaces [J]. Mathematical and Physical Sciences, 1966, 295(1442): 300-319.

2. BURDEKIN M, BAEK N A. Analysis of the local deformation in machine joints [J]. Mech. Eng. Sci., 1979, 34(3): 15-17.

3. HUANG Yumei, FU Weiping. Research on the dynamic normal characteristic parameters of joint surface [J]. Journal of Mechanical Engineering, 1993, 29(3): 74-78.

4. DONG Guanhua, YIN Qin, etc. Research on Dynamics Modeling and Identification of Machine Tool Joints [J]. Journal of Mechanical Engineering, 2016, 52(5): 162-168.

5. LI Ling, CAI Anjiang, etc. Micro-contact Model of Bolted-joint Interface [J]. Journal of Mechanical Engineering, 2016, 52(7): 206-212.