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Wear Analysis on Cylindrical Cam with Flexible Rod

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Abstrct: Firstly, the kinetic equation of spatial cylindrical cam with flexible rod has been established. Then, an accurate cylindrical cam mechanism model has been established based on the spatial modeling software Solidworks. The dynamic effect of flexible rod on mechanical system was studied in detail based on the mechanical system dynamics analytical software Adams, and Archard wear model is used to predict the wear of the cam. We used Ansys to create finite element model of the cam link, extracted the first five order mode to export into Adams. The simulation results show that the dynamic characteristics of spatial cylindrical cam mechanical system with flexible rod is closed to ideal mechanism. During the cam rotate one cycle, the collision in the linkage with a clearance occurs in some special location, others still keep a continuous contact, and the prediction of wear loss is smaller than rigid body.

Keywords: Cylindrical cam, flexible mechanism, kinematics characteristics, wear

I. INTRODUCTION

As we all know, the mechanical system direction of development is the high-speed, heavy-duty and precision, there is not much parts can meet the characteristics, but the cam is one of them, then more and more drive system use cams, the greatest advantage is to achieve high-speed, scompact body structure, high reliability, long life, movement and stop are very stable. Even if you change the speed can be kept in pace. Many scholars also studied on the kinematics of cam mechanism. Zhang Jun, Zong Zhenhua [1] have been studied on the kinematics of cylindrical indexing cam mechanism, established the dynamic equations under considering the clearance and flexible rod, then using finite difference method to solved it. Bo Yucheng, Xu Jian [2] and others were analyzed on the high-speed anti-cylindrical cam mechanism's kinematics of the roller under pure scroll. In order to avoid non-rolling state during exercise, to judge and analysis cam body's angular acceleration can obtained cam motion, it can provide an effective solution. Jin Guoguang [3] researched on high speed cam mechanism, combining modal synthesis technology and kane equations establish rigid coupling cam system dynamics model and analyzed the dynamic performance. HUSTON RL [4], he discretized the cam follower firstly, then established elastic dynamic equation of cam system according to Kane equation. However, they did not consider the effect of cam flexible mechanism. In many cases, we calculated cam wear under rigid condition [5-6], to find wear forecasting method on this basis, Chen Xinqiang [7] selected classical Archard wear model to calculated wear, and use software Matlab to development of the internal combustion engine's cam wear prediction software. TangQin use Zhang Yi Cheng's research to opened up new ways, it is that the wear simulation predictions of cam – hold are based on the principle of friction work [8-9]. In the cam mechanism under the high-speed movement, due to the inertia load mechanism, elastic deformation and clearance, it will have the collision between the member and the vibration. This will greatly affect the dynamics of institutions, as organizations wear during operation, this effect is more serious. While many people use the flat cam as the study object , but there is a big different between space cam and flat cam in the mechanism, they can't use in the same way. This paper will use the cylindrical cam mechanism for the study, because of the cam 's stiffness is much greater than the cam follower, it has a minimum response to the follower end, so we will be assumed the cam to be the rigid member[10]. Considering the cam follower as the flexible rod, then research on the kinematics characteristics and the cam wear, there is some significance in the practical applications, it can provide actual reference to development of the space cylindrical cam mechanism wear forecast softwear.

II. BUILD THE DYNAMIC MODEL UNDER THE FLEXIBLE ROD

1. setting cylindrical cam's parameters

In this paper, we use cylindrical cam, the part we can see in common life, the cam's push travel angel is $\emptyset = 144°$, the far angle of repose is $\emptyset_s = 0°$, the descend angle is $\emptyset' = 144°$, near angle of repose is $\emptyset_s' = 72°$, cam follower lift is $h = 150mm$, radius of base circle is $R_b = 110mm$, radius of roller is $R_r = 20mm$, allowable pressure angle is$[\alpha] = 25°$. Follower motion rule adopts cycloidal law of motion. Among them, the sports segment occupied the 1/8 of whole story to push away, that is $\emptyset_1 = \emptyset_2 = \emptyset/8$. By entering the data parameter theory contour, contour generation theory. As the follow figure 1.

Fig. 1 Three-dimensional model of cylindrical cam

2.The establishment of dynamics model

Under the condition of in spatial CAM high-speed operation and has a certain stiffness, namely, as shown in figure 1 of the cylindrical transmission. Considering the shaft torsional deformation affect the movement characteristics of the system. Therefore, this paper argues that the shaft of the flexible shaft. In spatial cylindrical CAM mechanism dynamics model is established, the assumption of the motor output must be, ignore the influence bending deformation of shaft, the axial deformation and drive motor characteristic factors on the system. Through the above hypothesis, the dynamic model are shown in figure 2 below. By lagrange theorem available type (1).

$$\begin{cases} m\ddot{s} + k_1 s + c_1 \dot{s} = F \\ J_1\ddot{\varphi}_1 + c_3\dot{\varphi}_1 + M_r + k_2(\varphi_1 - \varphi_2) + c_2(\dot{\varphi}_1 - \dot{\varphi}_2) = 0 \\ J_2\ddot{\varphi}_2 + k_2(\varphi_2 - \varphi_1) + c_2(\dot{\varphi}_2 - \dot{\varphi}_1) = \frac{P_0}{\dot{\varphi}_2} \end{cases} \tag{1}$$

where: s—actual displacement of the cylindrical CAM follower

φ_1、φ_2—the actual angular displacement CAM body and gear reducer(rad)

m—the quality of the follower connecting rod(kg)

J_1、J_2—the equivalent moment of inertia of the CAM and reducer（kg·m2）

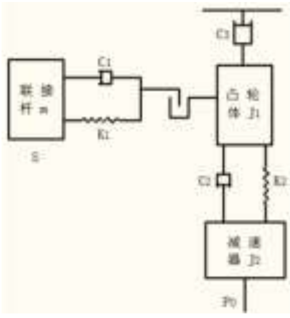
k_1、k_2—the torsional rigidity of CAM shaft, gear reducer shaft（N·m·rad-1）

c_1、c_3、c_2—the damping coefficient between follower and CAM, CAM and gear reducer.（N·m·s·rad-1）

P_0—the output power of gear reducer（N·m·s-1）

F—the driving force of the follower（N）

M_r—the impedance of CAM body（N·m）



eFig. 2 Dynamic model figure

3. The determination of contact collision force model

Defined in the Adams simulation process of the collision force method has two kinds, one kind is compensation method, other is a shock function method. Because of the former parameters is difficult to accurately set. Therefore, this article choose the latter define collision force, contact force model is determined by IMPACT function. In the process of calculation, when the depth of the collision of the contact model not to 0, namely $\sigma > 0$, activation function times, it found that the contact force by the rigid contact force and viscous drag in two parts. Its expression is as follows (2)

$$F_n = \begin{cases} k\sigma^n + \mathrm{step}(\sigma, 0, 0, d_{max}, c_{max})\dot{\sigma} & \sigma > 0 \\ 0 & \sigma \le 0 \end{cases} \tag{2}$$

where k is contact stiffness coefficient, depending on the nature of the contact materials and contact objects radius of curvature. k is obtained by the following formula (3)

$$k = \frac{4}{3(\sigma_i + \sigma_j)}\left[\frac{R_i R_j}{R_i + R_j}\right]^{1/2} \tag{3}$$

where $\sigma_i = \frac{(1 - v_i^2)}{E_i}$, $\sigma_j = \frac{(1 - v_j^2)}{E_j}$,

R_i, R_j are the radius of the two contact bodies, V is for two contact material poisson's ratio, E is the modulus of elasticity of two materials, N said deformation characteristics of index, steel 1.5. In the Adams simulation movement, the Step function show the collision depth increases, formula (4) as fol$\mathrm{step}(\sigma, 0,0, d_{max}, c_{max}) =$

$$\begin{cases} 0 & \sigma \le 0 \\ c_{max}\left(\frac{\sigma}{d_{max}}\right)^2\left(3-\frac{2\sigma}{d_{max}}\right) & 0<\sigma<d_{max} \\ c_{max} & \sigma \ge d_{max} \end{cases} \tag{4}$$

where c_{max} is maximum damping coefficient, the general value is 0.1% of the stiffness coefficient k, d_{max} is the maximum contact depth, this value is 0.01 in this paper. STEP function is shown in the figure 3 below, it says wear from zero to maximum contact depth increasing process.

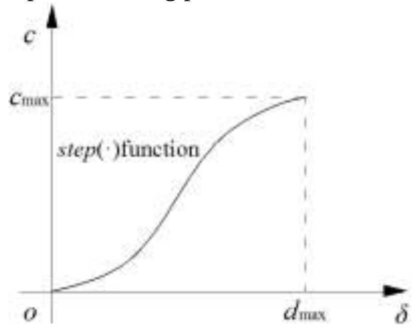


Fig. 3 Step function diagram

4. Tangential friction model

Generally, compared to the radius of curvature of the profile of CAM roller radius is very small. Roller moved in the CAM groove, considering of cylindrical CAM groove boundary friction, clearance contact feature uses the tangential friction model representation. In Adams software model, the tangential friction force use famous Coulomb friction model, the expression type (5) as follows[11].

$$F_\tau = -\mu(v_\tau)F_n\frac{v_\tau}{|v_\tau|} \tag{5}$$

where v_τ is the relative tangential velocity, F_n is the normal contact force, $\mu(v_\tau)$ is the dynamic friction coefficient, associated with tangential sliding velocity, and can be determined by the following formula (6).

$$\mu(v_\tau) = \begin{cases} -\mu_d \mathrm{sign}(v_\tau) & |v_\tau| > v_d \\ -\left\{\mu_d + (\mu_s - \mu_d)\left(\frac{|v_\tau|-v_s}{v_d-v_s}\right)^2\left[3-2\left(\frac{|v_\tau|-v_s}{v_d-v_s}\right)\right]\right\} \mathrm{sign}(v_\tau) & v_s \le v_\tau \le v_d \\ \mu_s - 2\mu_s\left(\frac{v_\tau+v_s}{2v_s}\right)^2\left(3-\frac{v_\tau+v_s}{v_s}\right) & v_\tau < v_s \end{cases} \tag{6}$$

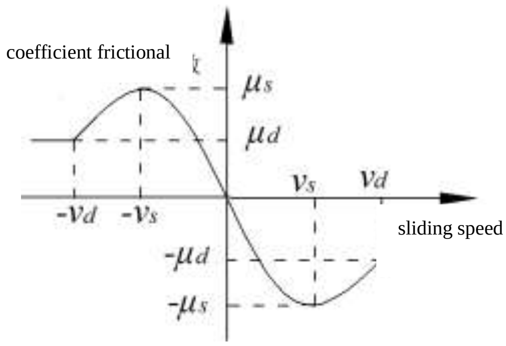
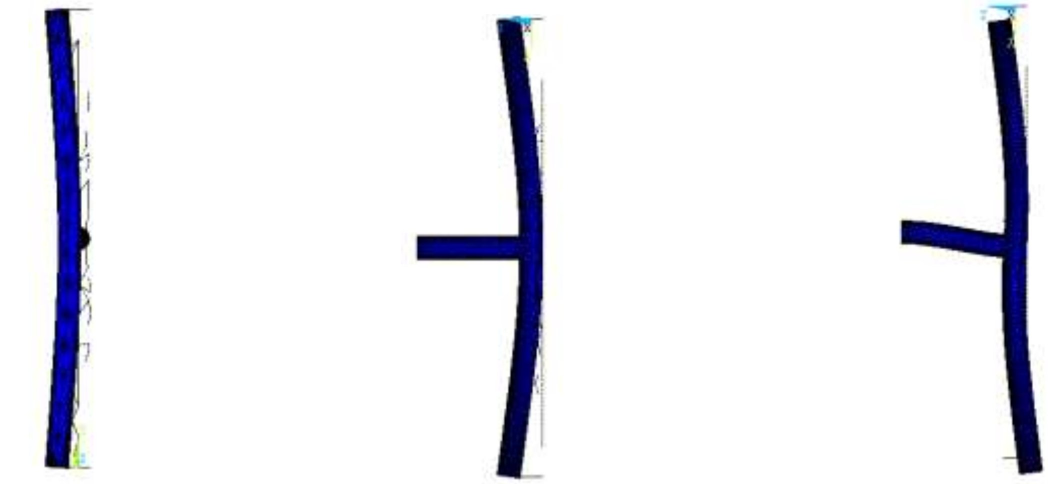


Fig. 4 modified Coulomb friction model

5. The flexibility for links of the mechanism

When we think that the follower of cylinder cam is a flexible mechanism and model it with the solidworks software. The moving bar of cam couple is cylinder which diameter is 30mm. We creat flexible axis of follower through introduct 3-d model by Ansys software. Setting cam follower feature by Ansys software as following: Elastic Modulus 1.7×10^{11}pa, Poisson's ratio 0.3, Quality ratio 7800 kg/m^3. Meshing this model use the Solid185 unit and displaying the first five orders of modal parameters natural frequencies, as this figure 5 showing. Establishing rigid-flexible coupling cylinder cam mechanism by introducing flexible bar through adams software, as the figure 6 showing.

(a) The initial state of flexible shaft
(b) The first order modal frequency is 94.5HZ
(c) The second order modal the frequency is 98.15HZ



(d) The third order modal frequency is 174.18HZ
(e) The fourth order modal frequency is 252.16HZ
(f) The fifth order modal frequency is 394.37HZ

Fig. 5 Flexible shaft's natural frequency and mode

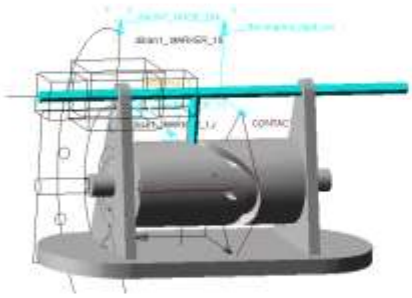


Fig. 6 Simulation figure of cylidrical cam

III. ESTABLISH WEAR MODEL

We have many versions on the principle and model of adhesive wear, many people like: Holm、Archard、Bowden、Tabor、Bucly had researched on it. In this paper, we choose the wear model of Archard who expressed metal volume wear by using yield stress and slide distance which many scholars have admitted it. The surface of solid is uneven, so it at least have three point contact even through under a small force. Incresing load, the contact area expands by two methods : enlarging the area of original contact points and increasing the nunber of new contact points.

The expression of the wear model of Archard as following:

$$W_v = \frac{KLS}{H} \tag{7}$$

There: W_v is metal wear volume; K is adhesion wear coefficient; L is normal load; S is slide distance; H is hardness of soft materials.

We can get wear depth through type (7) divided with contact area and type (8) showing.

$$h = kps \tag{8}$$

There: $k = K/H$ is linear wear coefficient, the value is $5.05 \times 10^{-4}\mathrm{mm}^3/\mathrm{Nm}$. However, the contact point and form of kinematic pair are constantly changing. The contact load and slide distance of contact point at different time, so change the type (8) as differential form like type (9):

$$\frac{dh}{ds} = kp \tag{9}$$

The actual calculation process using finite element method, considering the movement distance of space cylindrical is Δs. During this time, we can think the contact form of cam are the same. So the wear depth can be expressed as following:

$$h_i = kp_i \Delta s_i \tag{10}$$

There: p_i is contact stress, Δs_i increment of slide distance, as following: $\Delta s_i = s_i - s_{i-1}$.

Since the research object is a cylindrical cam mechanism, the contour lines generate by the cam groove, the sliding distance of the cam at each stage is different, so the calculation is diffrerence at each stage. This paper has a acceleration stage of cycloidal cam, intermediate stage of cycloidal motion, the deceleration phase of cycloid motion and the return period.

IV. THE RESULTS AND ANALYSIS OF SIMULATION

1. Kinematic analysis of flexible mechanism

In order to get more accurate simulation results, setting the simulation parameters as table 1 :

Table 1 The settings of simulation parameter

parameters	value
elastic modulus(E/pa)	2.1×10^{11}
stiffness coefficientkn (N/mm)	2.55×10^{7}
Speed of cam (rad/s)	50
The max damping coefficient	0.01
The max penetration depth	0.01
The length of the connecting rod (mm)	1000
The quality of link (kg)	6.17
The quality of cam (kg)	133.20
The quality of floor (kg)	6.84
poisson ratio	0.29

In this simulation, setting the parameters of this flexible mechanism like those as the rigid mechanism, we contrast the ideal rigid structure to analyze the dynamic characteristics, this purpose to obtain the characteristics of flexible mechanism that effect on the dynamic of cam mechanism. We get curve picture like figure 7 by the way of selecting link centroid coordinates of cam follower in this simulation, the displacement curve of this rigid follower and the flexible follower are basically identical. The driven member displacement amplification curves shown in figure 8. The two curves have a certain deviation that the maximum deviation is 5.62mm. We know that the displacement is least effected when the cam follower is flexible. The speed curve of this flexible follower exist large fluctuations , we can see it from figure 9, the rigid structure have large velocity fluctuations when the rigid bodies accelerate to a limit position as the cam follower have a greater collision groove wall, we obtain a smoother curves when the follower is a flexibility body. Enlarge the figure of follower velocity we can get the maximum deviation nearly 16mm / s. The speed curve of follower which we obtain also have some flexible fluctuations, as show in figure 10. Figure 11 is the acceleration of follower, when compare it with the rigid flexible follower ,the acceleration basically in a relatively smooth position only in several locations have a shock style jump and achieve maximum peak acceleration nearly 5.45m / s^2. Figure 12 is the contact collision picture of flexible follower , and acceleration curve of the flexible mechanism forces show the same characteristics, there are also consistent with the position of the pulse. In summary, under the same conditions to consider the dynamic characteristics of flexible link gap mechanism compare to the rigid institutional mechanism, the maximum deviation are the displacement and speed , the amplitude of acceleration shock and contact are reduce in same certain degree. In a movement cycle, when the cam follower move to a extreme position, creating a greater impact at this time for the direction change, while in other continuous areas, one end of the connecting rod and the cam groove to maintain continuous contact with the wall, its dynamic characteristics structure largely tends to be ideal, therefore, flexible follower greatly reduces the severity of collision with the cam during this movement, so that the motion characteristics of mechanism are more reasonable.

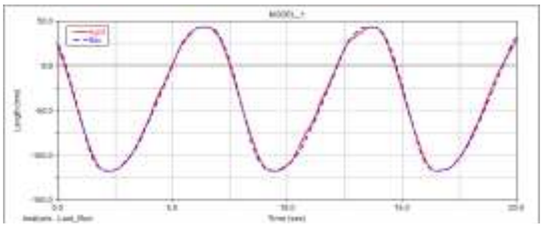


Fig. 7 Displacement of cam follower

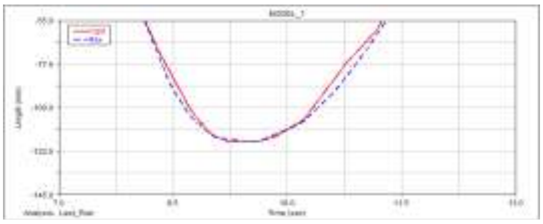


Fig. 8 Enlarged displacement of cam follower

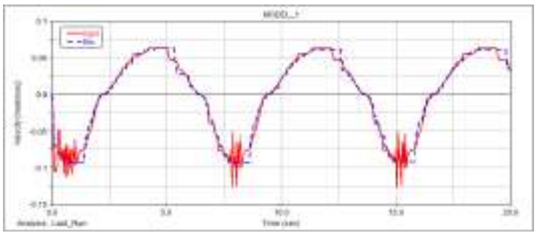


Fig. 9 Speed of cam follower

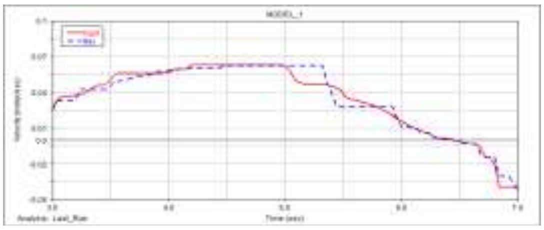


Fig. 10 Enlarged speed of cam follower

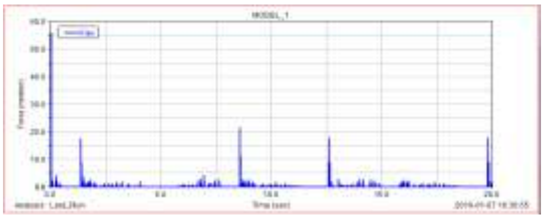


Fig. 11 Acceleration of cam follower

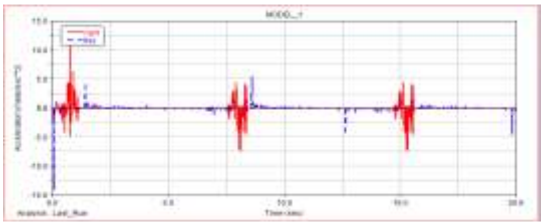


Fig.12 Contact force between cam and roller

2. The wear analysis of flexible mechanism

When research the problem of cam wear, especially study the wear rate, we usually only consider the wear rate of the end contact face between the follower and cam, and this is an important factor to effect the cam utilization in same great degree. However, like the cylindrical cam and some parts which have groove, they are two boundaries ,when they together with follower, it can creat friction and wear that is a mayor factor to effect cam utilization ratio. Screaming and vibration will occur and this phenonenon will be strengthen when mechanical is operation, this instability will be intensified when the part wear continuing, eventually, the component will fail.

To the high precision cam mechanism which dynamic characteristics can be effected by friction and wear. Compared with this cam that study in the paper, the edge of cam profile edge contact with the point and line of ejector pins are simple in the plane cam mechanism. In this paper, the most important feature of this spatial cylindrical cam mechanism is commutation in limit position, that is say when both ends of the cam follower reaches to the limit position, its moving direction would change, but due to the existence of the cam gap, this lead to the contact position change for the roller and the cam groove wall, so if we calculate the friction and wear flat of cam mechanism that is not accurate. Selecting a cycle cam movement to predict the wear of rigid and flexible bodies according to the law of Archard, that can be able to well analyze the cam mechanism. We can get the depth of wear of the cam roller as show in figue 13, when the cam follower are the rigid and flexible respectively. In the initial stage of the movement means have a greater impact, that leading to a sharp increase about the amount of wear, when the progress of the movement exist, cam contacting is stable that lead to collision force reduce. When considering follower of the flexible shaft, the movement trend of the two curves are the same, but when we considering most of the lever contact area is flexible, the dynamic wear greatly reduce and continuous contact state is more evidence, this phenomenon would reduce more than 40 percent compare to the station of rigid mechanism.

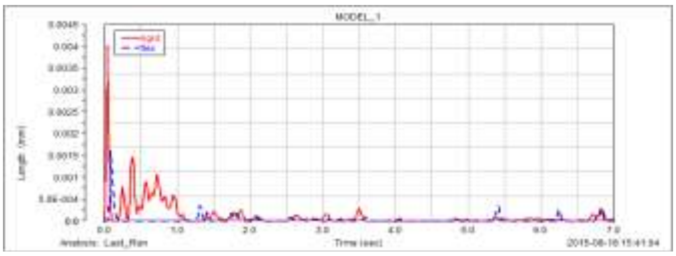


Fig.13 Wear depth

V. CONCLUSION

(1) The accuracy of the cam particularity influence on the simulation results for the special of cylindrical cam mechanism, thus rendering precise cam mechanism in three-dimensional space, and then model rigid and flexible cylindrical cam mechanism to research flexible institutions influence on the dynamic characteristic of systerm. Simulation results shows: when considering the impact of space cylindrical cam follower, cam acceleration is maximum factors, second is speed, the smallest is displacement. Cam groove with the presence of the roller gap, resulting in a collision and impact when institutions exercise, this phenomenon is obviously at the time of the cam follower commutation, however the flexible follower can well undermine the collision and the impaction that lead by the gap of cam, and easing the material wear and tear which caused by collisions. As the dynamic characteristics of cam can actually state tends, we can see the flexible of cam follower real state the motion reaction of cam link. It is a important significance to similar cam mechanism systematic study of dynamic motion characteristics.

(2) The more cam mechanism kinematics close to reality, the more accurate to wear simulation of cam mechanism, when the lever rigid flexible state income is less than the depth of wear which can obtain from comparing with the wear depth of rigid and flexible bodies. This can reduce the wear and tear of materials when the mechanism is flexible. In actually, when we forecast the friction and wear on mechanism, if considering the flexible station we can get a more accurate and reliable predictions.

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