Recoil and assembling clearance on roller dynamic analysis for cylinder cam mechanism

Jian Xu1,3, Lanwei Song2, Zhen Yang1 and Qiang Li1

1 North University of China, Taiyuan 030051, People's Republic of China
2 No. 208 Research Institute of China Ordnance Industries, Beijing, People's Republic of China
3 E-mail: zdp12_0@126.com

Abstract. In order to give the clearance and assembling recoil to the fixed cylinder cam mechanism, the main roller was dynamic analyzed. The system dynamics was done and the force changes quickly on the main roller and the force has a great value. Assembling clearance between the main roller and the cam curve slot, the main roller can suddenly rotate and it can reverse in several short intervals in theoretical analysis and test experiments, so that the huge friction force in the extremely short time will be the main wear factor. So that the main roller does not necessarily rotate in its validity period, and we are a kind of alarm of rolling or not.

1. Introduction

The conventional design of cylinder cam and roller follower mainly focuses on how to optimize the working part’s movement regularity, how to rationally arrange the movement cycle, among others studied this topic [1-3], and to check whether or not the follower keeps in contact with the cam and the usage of the conjugate cam mechanism, among others, Wen-Tung Chang studied this topic [4]. others [5-7] mainly is interested in the elastic or plastic response when the cam runs for a high speed. But there has relatively little research on the interaction between the cam curve and the working part roller system. This paper originally deduces the main roller’s pure rolling necessary condition in one type of recoil cylinder cam with clearance, and the calculation is done.

Figure 1. Cam curve slot mechanism and working parts structure (1- mechanism carriage 2- buffer 3- box mechanism 4- fixed cam curve slot 5- main roller 6- working parts 7- barrels).

Figure 2. Cam transmission mechanism (1- fixed cam curve slot 2- main roller 3- working parts 4- revolving body).
2. Gatling guns and main roller kinematic analysis

In this paper, a special cam mechanism is introduced. The mechanism is as Figure 1 and the cam curve slot and working parts are shown as Figure 2, the cam curve slot and working parts specific structure are shown as Figure 3.

![Figure 3](image-url) Working parts (1- working part body 2- main roller 3- main roller axis).

![Figure 4](image-url) Velocity decomposition for the main roller (1- cam curve slot 2- main roller).

In this mechanism, the cam is fixed with the framework and does not rotate in duty state, and a revolving body which is coaxial assembled has a longitudinal rail on its cross-section, the working part also has guide rail which mates with the rail on the revolving body.

And the working part has an axis which joints with the main roller which runs along with the cam curve slot as shown in Figure 2. In the working status, the revolving rotates along its axis, so the working part not only rotates with the revolving body in synchronism but also moves fore and after the rail on the revolving body. And the distinguished merit of the mechanism lies on that the designer can place several sets of rails and working parts along the circumferential direction as needed in order to work with high efficiency.

The working part is of high speed and heavy load transfer motion mechanism, they are very important. It not only relies on the cam curve but also determines the working part’s movement regularity. Thus it is the critical part of the cam design, and the transfer motion diagrammatic sketch is shown as Figure 4. The main roller force action must be strict and the main roller rolling state must be taken into account.

From Jian Xu [1], he researches the main roller kinematic analysis and the main roller pure criterion can be deduced:

\[
\frac{1}{A \cos \theta - B \sin \theta} \left[ (A \sin \theta - B \cos \theta) + \frac{CR}{f_{\alpha}} \right] > \frac{1}{f_a}
\]

All symbols have their definition in the article [1].

The Equation (1) is the necessary condition of the main roller pure rolling that is the paper present. To the designed cam roller mechanism, it may use this formula to check the design quality, because the \( \theta \) is the function of the revolving angle \( \phi \). Thus the designer can know whether or not the main roller is pure rolling on the corresponding \( \phi \). Furthermore, in the design process, the designer can adjust the layout of the cam curve to make the main roller pure roll in the heavy load region.

The main roller can be seen as a round plate which has the thickness \( t \), density \( \rho \), outer radius \( R \), and inner radius \( R_\text{i} \), its rotary inertia \( J \) is as Equation (2):

\[
J = \frac{1}{2} \rho \pi t (R^4 - R_\text{i}^4)
\]

With the \( A \cos \theta - B \sin \theta > 0 \), it yields the follows:

\[
\frac{f_a}{A \cos \theta - B \sin \theta} \left[ (A \sin \theta - B \cos \theta) + \frac{CR}{f_{\alpha}} \right] > 1
\]
Where: \( F_{ta} = \frac{1}{2} \rho \pi \tau (R^2 - R_e^2) \times \frac{1}{\sin \theta} \times \frac{d \epsilon}{d \phi} \times \left( \cot \frac{\theta}{\sin \theta} \times \frac{d \theta}{d \phi} + i \times \frac{d \epsilon}{d \phi} \right) + i \times \epsilon_i \times R \sin(\theta) \)

From \( J \) it can see that the decrease the main roller’s thickness \( t \), increasing the inner radius \( R_e \), decreasing the outer radius \( R \), does good to pure rolling and thus it can reduce the friction power consumption.

Thus the main roller pure criterion can be deduced.

3. Systems mechanism kinematics analysis

As Figure 1 shows that the mechanism can be running with launch, without considering the influence of recoil movement to cam mechanism, the cam curve slot transfer motion to the working parts as the common movement: in the accelerated period, the force acts on the push action surface, on the acceleration to 0, the force pushes into disappear, and because of the clearance, the main roller runs to the other cam curve envelope plane and crosses impact.

As Figure 1 shows that the cam curve slot when fir loads, the cam slot and working parts recoil after the acceleration of recoil, while in the process of pushing movement is pushing the bullet into the working parts, in the shell group process of movement, the working part is doing shell and cartridge.

In this case, in a set of acceleration movement \([8, 9, 10]\) is greater than 0, this is forced out of roller surface and it pushes across the envelope surface impact, so as to affect the movement of group movement, system resistance moment at the same time.

3.1. Analysis of three states

Figure 5 shows the face-to-face contact process of the main roller and the cam curve slot. To Figure 5, the contact force \( F \) converts direction, and the same equations are got. And with the reason [9], the force is not drawn up.

![Figure 5](image1.png)

**Figure 5.** Three status of the main roller (1- cam curve slot 2- main roller).

According to Figure 5 and the direction of \( F \), and the results can be got:

1. A status, the \( F \) can make the main roller clockwise, and the differential equation can be:

\[ J \epsilon = F \times R \]  \hspace{1cm} (4)

2. B status, the clockwise can be reached, but the effect is \( F_f \), the rotate angle velocity decreases, and the differential equation can be:

\[ J \epsilon = -F_f \times r \]  \hspace{1cm} (5)

3. C status the main roller, and with the friction \( F \), the rotate angle velocity decreases, and the differential equation can be:

\[ J \epsilon = -F \times R \]  \hspace{1cm} (6)

Then Equation (6) is being discussed: if longer exposure can be reduced to the variable rotation speed clockwise counterclockwise 0. If the contact time is short, the main roller will keep moving in

![Figure 6](image2.png)

**Figure 6.** Influence of relative movement to motion cam curve slot.
the same direction, and the box mechanism moves forward, will be out of contact, and then back to the A contact state. The duration of the exposure is closely related to the movement of the recoil box mechanism, directly associated with the design of buffer. Therefore, in the A state to the C state main roller brakes and then reverses acceleration, accompanies by the wear of cam curve slot. Therefore, it usually sees the cam curve slot is not strictly in accordance with the acceleration and deceleration of inverse transmission contact surface wear, but the cam curve slot on both sides have experienced wear.

3.2. Several working parts forward and reverse drive transmission with recoil
The main roller with clearance and the cam curve slot driving system of the box mechanism will not only enter the reverse drive state in advance but also have a sudden change in their own rotation state under the action of the backseat caused by the launching load [10].

To illustrate the problem, it takes the 4-barrel mechanism as an example to illustrate the problem, as shown in Figure 6:

4 sets of working parts layout as shown in Figure 6, the 1, 2, 3, 4 position, 1, 3 position is being pushed, corresponding acceleration and ejection acceleration, 2, 4 position inverse transmission, corresponding to push deceleration and ejection deceleration stage.

Considering the gap between the main roller and the cam curve slot respectively, as shown in Figure 5. In the emission load and buffer device, box mechanism and fixed on the cam curve slot as shown in the direction of the arrow recoil, it occurs on the main roller of two 1, 4 from the gap position, after the advance into the inverse transmission state, and relies on the position two 2, 3 is not out, and keeps the oppression of the state, the current instantaneous state into only one main roller 3 positive drive, three main rollers 1, 2, 4 into drive or drive from the inverse state in 1 cycle, and this routine analysis does not consider the gap and the cam curve slot with the box mechanism with recoil is different.

If the frequency is very high, very fast recoil motion vibration is in the 1, 4, and not across the surface contact cam envelope before reversing and recoil motion, then the main roller must exist as shown in Figure 5 the B position shown in intermediate free state the same. Any other box mechanism can analysis and so on.

4. Example verification
4.1. Test method and basic structure
Because of the particularity of Gatling weapon, the acceleration test of the machine needs to adopt the storage test technology, because of the limitation of the structure, the volume of the storage test is required to be higher, so it is necessary to design the storage test device with a smaller volume. As to be able to be installed in the existing core head, the structure of the actual core heads is improved so that the device can be installed in the core head. It is hard to begin the experiment as beginning because it is hard to begin the experiment because the main roller axis is also rotated as Figure 7, so we have to Figure 8 experiments. Because the main roller axis is also rotated, it has been to measure the acceleration of bolt, conversely, we have to introduce the main roller rotate station [11-16].

![Figure 7](image1.png) **Figure 7.** The main roller rotate experiment (1- graduated arc 2- main roller axis).

![Figure 8](image2.png) **Figure 8.** Test device structure (1- bolt body 2- storage test device 3- bolt head 4- acceleration sensor 5-fixed lid).
The choice of acceleration sensor: according to the theoretical analysis, the maximum acceleration is $5000 \text{m/s}^2$ at the highest firing speed, and the range of the acceleration sensor is $20000 \text{m/s}^2$. The test trigger mode is an internal trigger, when the acceleration is $100 \text{m/s}^2$, according to the requirement of test time, the storage capacity is designed to meet the test time of 2 s. The storage capacity takes into account the test time from startup to stable speed.

And with the frequency of sampling of 200KHz, the result is like Figure 9, its result like Figure 10(a), Figure 10(b), and Figure 11, Figure 12 is the frequency of sampling of 50KHz, the bolt movement acceleration measure curve: and the acceleration in Figure 12 is like Equations (4)(5)(6), it shows the main roller cuts across the cam curve slot.

Figure 9. Gatling Bolt acceleration of 200KHz.  
Figure 10. Comparison of periods of test acceleration.  
Figure 11. Gatling Bolt acceleration of 50KHz.  
Figure 12. Longitudinal directions compressed of Gatling Bolt acceleration.

This can be zero division operation and some elimination operation, this Figure 9 can reach the Figure 11 to reach 80%, with its result is the correct and correct method. These results also indicate the result of Figure 13, the contact force of the main roller (that is in the figure the contact_behind and contact_front) is one forward, others are one towards the back and others are none, thus it is clearance between main roller and the trajectory, there is also called assemble clearance, as Figure 11 and Figure 12. So that the friction of the cam curve slot is caused by the rapid change of the main roller.

From Figures 9-12, the processed pictures are as for Figure 13, which is like Figure 10 and Figure 11, the image hook is particularly similar:
4.2. Some case analysis
Considering the dynamics model of the main roller and cam curve slot and clearance must be considered, the model has the cam curve slot and rotary mechanism and working part, and the recoil is also needed.

In order to simulate the recoil movement under the transmitting load, the cam curve slot and the box mechanism are fixedly connected, so that a movable pair can be applied between the cam curve slot and the ground in order to simulate the recoil movement of the box mechanism; as for 14.5mm Gatling gun, shooting at 3000 rpm, the box mechanism recoil displacement vs. time as Figure 14, and it is between from -6 mm to 12mm.

Figure 14. Gatling gun recoil displacement vs. time curve.
Figure 16. Without recoil contact force without consideration clearance.

Firstly, the no clearance between the main roller and cam curve slot, without consideration the recoil situation, using ADAMS software after the analysis, the result as Figure 15, and main roller displacement is also the working part body movement, as Figure 3. The contact force between the main roller and cam curve slot as Figure 16.

Secondly, the clearance can be taken into account, and without consideration recoil situation the result as Figure 17: and the Gatling bolt movement condition is as Figure 18, so the time can add to 0.5s, to see the acceleration of bolt.

Figure 17. Main roller about clearance without recoil.

Figure 18. Without consideration recoil of bolt movement.

Finally taking into account the recoil and assemble clearance and the result as Figure 19, Clearance influences on system transmission as Figure 20.
Figure 19. Clearance and recoil the working part.

Figure 20. Mall roller simulation with clearance 0.1mm recoil.

5. Conclusions and expectations

5.1. The original conclusions
(1) The pure rolling of main rollers is established, which is built by the cam curve slot and main roller structure. And the maximum acceleration of the working part should be as small as it could, this will be done by the cam curve slot, and it does an advantage to the friction and power consumption, but the inertia acceleration load does well to main roller pure rolling. Properly decreasing the main roller’s thickness, increasing inner radius and decreasing the outer radius did good to pure rolling and thus it can reduce the friction powers consumption.
(2) The face-to-face contact process of the main roller and the cam curve slot is built. Studied considering the movement towards clearance cam curve slot with recoil motion, it is proposed in consideration of recoil box mechanism case, and main roller cross-impact in advance and reverses drive for acceleration and deceleration limitation of inverse transmission.
(3) The main roller would drive from the inverse state while it operated 1 cycle. It pointed out that the wear of the cam curve slot is partly due to the driving pressure in transmission. The other main reason is the frequent braking and rapid reversing of the main rollers caused by the recoil motion, which provides a reference from a deep understanding of the transmission wear mechanism.
(4) This paper presents a simple emphasis that the recoil force and recoil displacement between the Gatling gun and buffer device because only a very good control of the transmission relationship to avoid the irregular and unpredictable the control.

5.2. Discussion and prospect
(1) Considering the clearance is essential because the main roller wears a degree and the main roller and the cam curve slot is of the equal size. If considering the inconsistency between the main roller
and the cam curve slot, there will be some inverse transmission, some have no conversion thus more things increase the resistance moment of Gatling gun. Further researches need the joint efforts of industrial power.

(2) Gatling gun to rotate around a high speed in the launch environment, and the sensor layout is difficult, so we need to the development of miniature sensors test device, especially, in the main roller rotating environment and the measurement results are lack of main roller action.

Acknowledgements
The authors are grateful to National Science Foundation of China Grant #51175481 and Hubei Sannong Science and Technology Talents Project 2020-2021.

References
[1] Xu Jian, Li Qiang and Yang Zhen 2016 Roller Dynamic Analysis and Pure Rolling Criterion for one type High Speed Cylinder Cam Mechanism Journal of the Chinese Society of Mechanical Engineers 37(4) 315-323
[2] Qiu Hua, Lin Changjun, Li Ziyi, et al. 2005 A universal optimal approach to cam curve design and its application Mechanism and Machine Theory 40 669-692
[3] Camara Amara and Han Xuli 2002 Approximation of the curves by b-spline Mathematical Theory and Application 22(3) 40-43
[4] Chang Wen-Tung, Wu Long-long and Liu Chun-Hsien 2009 Inspecting profile deviations of conjugate disk cams by a rapid indirect method Mechanism and Machine Theory 8 1580-1594
[5] Yan Hong-sen, Tsei Mi-Ching and Hsu Meng-Hui 1996 A Variable-Speed Method for Improving Motion Characteristics of Cam-Follower System ASME Journal of Mechanical Design 1186 8
[6] Chew M and Chuang C H 1990 Designing for Lower Residual Vibrations in High-Speed Cam-Follower Systems over a range of Speeds ASME Design Engineering Division Publication DE 26
[7] Liang Shirui 2007 Innovation of Automatic Weapon Peking: National Defense Press 234-236
[8] Nortan R L 1992 Design of Machinery-An Introduction to the Synthesis and Analysis of Mechanisms and Machines McGraw-Hill
[9] Xu Jian, Bo Yucheng and Chang Xuefang 2007 Analysis and Improvement of the Cam Curve Groove for Super-high Fire Rate Gatling Gun Journal of Gun Launch and Control 4 43-46
[10] Zhu Zhichao 2001 Roller Pure Rolling Dynamic condition for high speed cam mechanism Machine Design 4 4-8
[11] Zhang Youyun, Chen Zhao, Zhu Yongsheng, et al. 2013 Finite element simulation of effects of COF on wear of high pair Journal of Harbin Institute of Technology 9 64-68
[12] Wei Anci 1992 Relationship between friction coefficient and slipping speed Teach and Technology 1 1-3
[13] Wang Guoqiang, Ma Ruoding, Liu Juyuan, et al. 1997 Study on the Coefficient to Dynamic Friction between Frictional Metal Material Transaccons of the CSAE 13(1) 35-38
[14] Han Lichao 1998 A Calculation Formula of Static Frictional Coefficient of Sliding Bearings and its Practical Significance Journal Wuhan Univ. of Hydr. & Elec. Eng. 1 110-111
[15] Wang Zhicheng and Fan De'en 1988 An Analysis of Coefficient of Sliding Friction and its physical interpretation Journal of Shanghai Institute of Mechnical Engineering 1 65-73
[16] Gong Zhongliang and Huang Ping 2011 A calculating model of sliding friction coefficient based on non-continuous energy dissipation Acta Phys. Sin. 60(2) 389-39