Solutions optimization of decreasing rail friction for bolts mechanical power consumption

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Abstract. In order to save energy, several countries recently made laws related to mechanical power consumption. Motion Acceleration is known to affect the mechanism power. In order to reduce the minimal driving power, the gun bolts velocity and the main roller relative to whole body and the right-and-left rail and obliquity of rail are researched. The result indicates that the best situation is minimum acceleration of bolt group cam and the main roller relative to whole body is zero, and it is good in non-altitude difference with bilateral angle. The optimization results show that in the case of high rate it is very good to low rate, and the force prompt drops as the high fire ratio to low ratio.

1. Introduction
Mechanical power for cam mechanism also is very important, several prediction methods for reducing power consumption have been published [1-3], others mainly turned to cam curve design and to cam curve and main roller contact design, and to cam curve mechanism vibration and not to power saving. In order to set up lower driving power of Gatling gun’s bolt groups and drive more easy, it mainly research to drive more easy and handily the way of the bolt’s acceleration, main-bolt relate to the bolt location, bolt bilateral lead rail and angle, some conclusions are gotten and give some references.

2. Bolt group acceleration

2.1. Bolt group acceleration
Gatling gun’s bolt maximum acceleration with the excessive angle can be replaced [2-3], and if the acceleration can be slowed down and the cam curve velocity don’t change obviously, then changing the cam curve can slow the power significantly:

\[ a_{\text{max}} = \frac{\pi m \theta^2}{2(\theta_A + \frac{\pi}{2} \theta_B + \theta_C)} \]

(1)

Where: \( m \) —rate of grade of inclined section; \( \theta_A, \theta_B, \theta_C \) —the angle allocation in the transmission section, \( \theta_A, \theta_C \) is the angle of the cycloid, and \( \theta_B \) is the parabola curve’s angle which links \( \theta_A, \theta_C \) which is shown as Table 1:
Table 1. Layout contrast of cam curve fore and after improvement.

| Transmission angle | Feed inclined angle | Front dwell angle | Eject inclined angle | Rear dwell angle |
|-------------------|--------------------|------------------|---------------------|-----------------|
| Unimproved        | 19/20              | 84               | 95                  | 71              | 32              |
| Improved          | 72.5               | delete           | 70                  | delete          | cancel          |

Conversely it can be deduced that the reducing maximum acceleration has advantage to power consumption. Table 2 shows the results for two kinds front dwell section layout but fire ratio varies which can be controlled by shot control box. The driving power can be considered that it has cubic relationship with fire ratio and it works better as the fire ratio rises.

From the Table 2, it clearly see that the 5000rpm percentage point reduces to original curve to 25% [4-5], and the 9000rpm firing rate, the power drop from 140kw to 31kw and slow down to original curve 22%.

Table 2. The bolts group' parameter contrast according to different fire rate.

| Scheme Variable | Unimproved | Improved |
|-----------------|------------|----------|
|                 | 9000r/s    | 5000r/s  |
| velocity (m/s)  | 15.76      | 8.75     |
| Acceleration( m^2 s^-2) | 5472.7 | 1689.1 |
| Power(kw)       | 140        | 24       |
|                 | 9000r/s    | 5000r/s  |
|                 | 23.82      | 13.2     |
| Acceleration( m^2 s^-2) | 2437.1 | 752    |
| Power(kw)       | 31         | 6        |

In the course of the bolt body pushing the bolt head, and in the point of acceleration reverse sign, the bolt body is restricted by the cam curve slot and is forced to decelerate, but the bolt head will keep its velocity due to inertia. And the relative movement between bolt head and bolt body will happen. The action plane will change and the collision occurs, the same time the main roller and the cam curve slot exists overstep impact. And the improved cam curve can also reduce the impact. Because the impact velocity [4-8], due to overstep impact is as follows:

$$v_{imp} = \sqrt{4.5 \left| j(t_0) \right| \delta^2}$$

(2)

where: $j(t_0)$—acceleration's derivative in the point of acceleration reverse sign, $\delta$ —the clearance between the bolt body and bolt head.

According to cam curve's expression, the formula to geometrical acceleration's derivative in the point of acceleration reverse sign can be described as:

$$j(t_0) = -\frac{\pi^2}{16} C_6 \left( \frac{\omega}{\theta_c} \right)^3$$

(3)

Where: $C_6$—coefficient in cycloid expression.

It provides that the unimproved $j(t_0)=-9.77e6m/s^3$, and the improved $j(t_0)=-1.28e6m/s^3$. If the collision velocity is 0.76m/s and 0.386m/s, it reduces to 50% and the impact force can be reduced greatly because of the very short impact time. Thus it can be seen the improved design will do good to impact condition.
2.2. Main roller’s relative to bolt body position \((x_0, y_0)\)

In order to get the value of \(x_0, y_0\), it needs to apply the Newton’s Second Law in the working part system: longitudinal direction (put the and project in the working part movement direction and form the active push force of as Equation (4) and the cross direction force as Equation (5) which is vertical to the movement direction.

\[
F_Z = N \cos \theta - F \sin \theta \quad (4)
\]

\[
F_r = N \sin \theta + F \cos \theta \quad (5)
\]

Where: \(N\) - the wall pushing force, that is \(F_N\), \(F\) - the wall’s friction.

Except friction force due to inertia force, others force and their layout can be sketched as Figure 1. The \(h\) symbol represents the distance from the main roller to the guide rail in the working part main body, and \(b\) represents the working part guide rail’s length, is the \(c\) working part main body’s width, and \(x_0, y_0\) is the distance from the main roller to the working part’s center of mass.

As shown in Figure 1, \(h = 30mm\) and \(b = 80mm\) and \(c = 60mm\), \(x_0, y_0\) is the displacement between main roller to center of mass of bolt group.

Push all the force to its longitudinal direction and get the differential equation [9]:

\[
ma = F_Z - 2f \frac{F_x h}{c} - 2f \frac{F_y h}{b} - 2f \frac{F_x x_0}{b} - 2f \frac{F_y y_0}{b} - f mr_1 \omega_1^2 - f m r_1^2 \epsilon_1 - f F_r 
\]

Where:

- \(a\) - working part’s longitudinal movement acceleration;
- \(f\) - friction coefficient between guide rail and working part;
- \(2f \frac{F_x h}{c}\) - friction due to front-to-rear overturn;
- \(2f \frac{F_y h}{b}\) - friction due to left-to-right overturn;
- \(2f \frac{F_x x_0}{b}, 2f \frac{F_y y_0}{b}\) - friction due to planer overturn which rises from main roller offset from the center of mass;
- \(f m r_1 \omega_1^2\) - friction due to working part centrifugal force;
- \(f m r_1^2 \epsilon_1\) - friction due to working part’s tangential inertia force;
- \(f F_r\) - friction due to cross direction force of \(F_r\).

Then:

\[
F_N = \frac{1}{A \cos \theta - B \sin \theta} [F(A \sin \theta + B \cos \theta) + C] 
\]

The cam curve and the pressure angle to angle of revolution are shown as Figure 2 [10-13].
Figure 2. The cam curve and the pressure angle.

The main roller has the thickness \( t = 6mm \), density \( \rho = 7850kg / m^3 \), outer radius \( R = 12.5mm \), inner hole radius \( R_n = 4mm \), the main roller’s equivalent revolution radius \( r_2 = 158mm \), and the working part equivalent revolution radius \( r_1 = 118mm \), the mass of working part \( m = 1.15kg \), the static friction coefficient between main roller and cam curve \( f_s = 0.12 \).

Suppose that \( x_0 \) variation range is \((-21, 21)\), \( y_0 \) variation range is \((-31, 31)\). Set with the 10 Gatling gun and set with revolving variable, and get the firing rate between with 3300rpm and 10000rpm, the main roller pressure with the main roller displacement \((x_0, y_0)\) as Table 3. That the \( x_0, y_0 \) variation range is very close to \( F_N \).

Table 3. Main roller layout active to fire ratio rpm.

| Fire ratio(rpm) | Min \( F_N \) (N) | Max \( F_N \) (N) |
|-----------------|-----------------|-----------------|
| 3300            | 913.7           | 1086.5          |
| 10000           | 8223.5          | 97793           |

3. Research on the structure of the body

Project all forces, which includes drive force and friction, due to inertia force in the working part’s movement longitudinal direction, and the Newton’s Second Law of the working part can be written as follows Equation (8) [9]:

\[
ma = F_x - 2f \frac{F_x h}{b} - 2f \frac{F_y (h - H \cos \alpha)}{c} \cos \alpha - 2f \frac{F_x x_0}{b} - 2f \frac{F_y y_0}{b} - f m r_1 c_1^2 - f m r_2 c_2^2 c_1 \\
- f r_1 \left( \frac{1}{\cos \alpha} + 2h \frac{\sin \alpha}{c} \right)
\]
Where: all others can seen in the differential Equation 6; \[ 2f \cdot \frac{F_c(h - H \cos \alpha)}{c} \cos \alpha - H \] leading to bolts left and right overturn’s friction; \( f \cdot \left( \frac{1}{\cos \alpha} + 2h \cdot \frac{\sin \alpha}{c} \right) \) -cross force leads to friction; The angle rotate is \( 18 \pi \) and displacement and angle of revolution is like Figure 3.

![Figure 3. Bilateral angle \( \alpha \) and bilateral height \( H \).](image)

It shows the bilateral angle \( \alpha \) and bilateral height \( H \) affects the situation of stress.

3.1. Computer Simulation

3.1.1. Bilateral angle \( \alpha \). Bilateral angle according to its scope, let it run as \([0^\circ \quad 20^\circ]\). According to its scope and use its and get the result as follows Figure 4:

![Figure 4. Bilateral angle \( \alpha \).](image)

3.1.2. Bilateral height according to its scope, let it run as \([0 \quad 20]\). According to its scope and use its and get the result as follows Figure 5:
3.1.3. Two condition with different condition. With $H = 20 \times 10^{-3} m$ and $\alpha = 25^0$, and $H = 0 m$ and $\alpha = 0^0$, and calculates to get the results Figure 6 and 7:

Figure 5. Bilateral height $H$.

Figure 6. $H = 20 \times 10^{-3}$ and $\alpha = 25^0$. 
3.2. Simulation results
Simulation results is shown as Table 4.

| Several layout | Layout $\alpha$ and $H$ | Maximum $N$ |
|----------------|-------------------------|-------------|
| First layout   | $25^0$ and $0\ m$       | 3056 N      |
| Second layout  | $25^0$ and $20*10^{-3}\ m$ | 2907 N     |
| Third layout   | $0^0$ and $0\ m$        | 2955 N      |
| Fourth layout  | $0^0$ and $20*10^{-3}\ m$ | 2778 N     |

Calculation results:
With bilateral angle $\alpha$ and bilateral height $H$, It is good to server $H=0$ and some $\alpha$. The condition may deduce 90.9% of the case of some $H$ and not $\alpha$. So in the practice, some machine gun has some $H$ condition, if the condition is high to plan and not bring pressure to leap, and what’s more, if the condition is very small to not think the layout.

4. Conclusions
All fourth methods reduce the gun’s bolt friction to some extent.
1. To use the bolt acceleration must minimum, also bring the minimum bolt acceleration and bolt group driving power minimum.
2. Main roller is good at center of mass of bolt group.
3. Bolt group is good at not $H$ and it has some $\alpha$.

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References
[1] Yu Zhizhuang, Dong Guangneng and Xie Youbai 2005 A new method to reduce frictional...
power consumption of piston ring in internal combustion engine *Lubrication engineering* 6 18-20

[2] 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* 8 315-323

[3] Liu Shu, Zhang Qing and Bo Yucheng 1999 The design of the cam curve for rotating multi-barrel machine gun *JOURNAL of North China Institute of Technology* 3 36-39

[4] Qiu Hua, Lin ChangJun, Li ZiYe 2005 A universal optimal approach to cam curve design and its application *Mechanism and machine theory* 40(6) 669-692

[5] Chang WenTung, Wu Longlong and Liu ChunHsien 2009 Insecting profile deviations of conjugate disk cams by a rapid indirect method *Mechanism and machine theory* 8 1580-1594

[6] Yan Hongsen, Tsei MiChing and HSU MengHui 1996 A variable-speed method for improving motion characteristics of cam-follower system *ASME journal of mechanical design* 118 6-8

[7] 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

[8] Nortan R L 1992 *Design of machinery-an introduction to the synthesis and analysis of mechanisms and machines* McGraw-Hill

[9] Engineering Design Handbook *Automatic Weapons* 1970 U S Army Material Command

[10] Dai Chengxun, Jin Tianyou and Duo Yingxian 1990 *Automatic weapon design* Peking: Press of national defense

[11] Xu Jian, Bo Yucheng and Chang Xuefang 2007 Analysis and improvement for cam curve groove for super-high fire rate gatling gun *Journal of gun launch and control* 4 43-46

[12] Xu Jian, Bo Yucheng and Chang Xuefang 2009 New type of low power consumption cam curve designed for super-high fire ratio gatling gun *Journal of ballistics* 2 70-73

[13] Xu Jian, Bo Yucheng and Li Qiang 2010 Research on main roller layout in bolt carrier for gatling gun *Acta armamentarii* 8 1036-1040