

# Firing Accuracy in Rotor Dynamics Prediction of Unbalanced Mass and Bearing Clearance

Jian Xu<sup>1, a, \*</sup>, Zhen Yang<sup>1, b</sup>, and Wanchuan Liu<sup>2, c</sup>

<sup>1</sup> North University of China, Taiyuan, 030051, P.R. China;

<sup>2</sup> Chongqing Jianshe Industry (GROUP) Co., Ltd, Chongqing, 400054, P.R. China.

<sup>a, \*</sup> 20050106@nuc.edu.cn, <sup>b</sup> yzhen@nuc.edu.cn, <sup>c</sup> lwq@nuc.edu.cn

**Abstract.** The XYZ center of gravity of the barrel part of the M134 Gatling gun and the components composed of bullets was calculated from the five types of clearances between the bearings without clearance to the bearings with clearance. According to the calculation of five clearances, the angle deviation is about  $11.5^\circ$ , and based on the target of 3000m, the sidelflight is about 600 meters. From the perspective of Gatling weapons, it has been officially determined that transfer weapons must primarily rely on surface killing.

**Keywords:** Unbalanced mass ; rotating mechanism; Surface kill; Vibration response; gapless.

## 1. Introduction

Other papers have studied vibrations that are rotating but perpendicular to the axis, as paper [1]. Hao Yang shows that depending on the hypothesis of Bernoulli-Euler[2-4] beam theory, the M134 Gatling gun has a firing rate as the dividing line. According to the Campbell diagram[5-9] for the M134 Gatling gun, if its rounds per minute(rpm) are lower than the boundary of 500 rounds per minute, the rotor is a rigid connection mode, and the rpm is higher than the parting line, it is a flexible connection. The M134 gating gun shows different rigidity and flexibility characteristics depending on the firing rate. Unbalanced rotor[10] was deduced by Wang, AM. He shows that rotor unbalance identification plays a critical role in balancing rotors. In his paper, concerned with multi-disc and multi-span rotor-bearing systems are introduced. Koo, Ja Choon[11] introduced a high precision rotor. The unbalanced mass of a high precision rotor deteriorates mechanical performance of the rotor. The geometrical center of a rotor generally corresponds to the rotational axis of the rotor. All these papers introduced the unbalanced rotor. But for us ,there is no rotor system in the field of national defence - Gatling gun. Therefore, this paper studies the vibration analysis on unbalanced rotor system based on Gatling gun.

## 2. Unbalanced mass on high-speed rotating mechanism

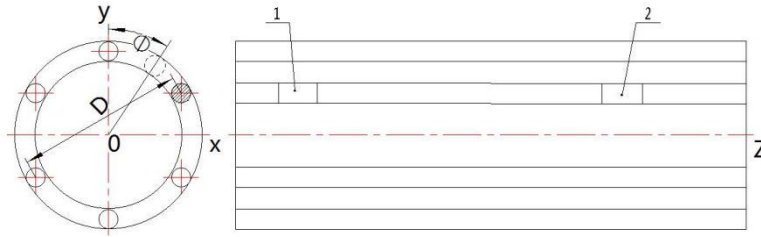
The M134 Gatling gun is as Fig.1, because the Gatling gun has a reputation abroad, all countries have transformed it. However, among all Gatling revolver guns, the United States has one of the most representative revolver guns: the Minigun, which is the M134 7.62mm revolver gun. This is a Gatling gun developed based on the M61 20mm aircraft gun used in the Vietnam War that year. It has six barrels and is driven by an electric motor to rotate the barrel. It is mainly used for the machine gun in the helicopter hatch. Sometimes they are also installed on infantry vehicles and naval ships.



Fig. 1 M134 Gatling gun

The Gatling gun, as a cantilever rotor was studied, and the axis coincides with the cantilever beam, as Fig.2. It calls a rotary squirrel cage cantilever[12]. There are bullets in the rotating barrel

machine gun, just like there is unbalanced mass in the rotating rotor, that is, the unbalanced rotor is rotating. Gatling gun is the unbalanced high-speed rotating mechanism



1-moving bullet 2-new position of the bullet  
 Fig. 2 Rotary cantilever structure with Z axis

It is 6 barrels Gatling gun, just as the bullet in the barrel. The first position is the position where the bullet has been fired, and the second position is the new position of the bullet, which is about to come out of the barrel.

To 2000 points, the calculation formula of  $I_z$  is as follows:

$$I(Z) = n * m_{zg} * \left(\frac{D}{2}\right)^2 + I_{zg} \quad (1)$$

Where:  $I_{zg}$  is the moment of the barrel connector and 6 barrels,  $m_{zg}$  is the mass of the barrel connector and the 6 barrels;  $m_{zg}$  is the mass of the bullet,  $n$  is the number of the bullet.

After calculation, its internal ballistic time is only 1.2ms. Only when the firing speed exceeds 5000 can two bullets be guaranteed in the barrel. The practical firing rate of M134 is 2000rpm, that is ,  $n=1$ ;

$$I(Z) = m_{zg} * \left(\frac{D}{2}\right)^2 + I_{zg} \quad (2)$$

According to the size of each part, the solid is drawn by 3D software, and then imported into the finite element software, which is divided by hexahedral mesh, and the calculated model is obtained.

### 3. No Bearing Clearance Condition

If the bearing clearance is zero and the barrel on the left is the zero point of  $xy$ , the gun body and the frame base are completely matched, thus the center of gravity of the barrel is :

$$L = m_{sg} * D / 2 / (m_{zg} + m_{sg}) \quad (3)$$

$$X = L * \sin(\Phi) \quad (4)$$

$$Y = L * \cos(\Phi) \quad (5)$$

$$Z = (m_{zg} * l_{sg} / 2 + m_{sg} * t_{sg}) / (m_{zg} + m_{sg}) \quad (6)$$

The gun has an rpm from 300 to 6000, and the time interval is 200ms to 10ms. By the time the second bullet was started, the first bullet was already out of the gun. There is no interaction between the first and second bullet. And two bullets do not appear in the barrels at the same time. The Gatling gun rotation rate is at Table 1:

Table 1. Gatling gun rotation rate

Gatling gun rpm	Speed of revolution round/s	Rotor speed(rad/s)
300	0.83	5.21
500	1.38	8.66
1000	2.77	17.39
2000	5.55	34.9
3000	8.33	52.3
4000	11.11	69.77
5000	13.88	87.17
6000	16.66	104.62

If the M134 fires at 2000rpm to 6000rpm, from Eq(3)-Eq(6), if the clearance is zero the barrels can vibrate as follows Fig.3-4:

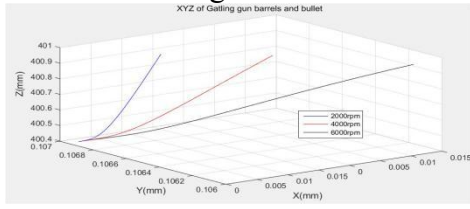


Fig. 3 Barrels vibration

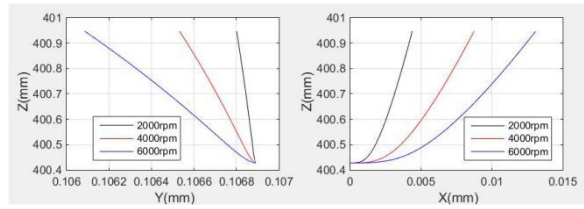


Fig. 4 Barrels vibration at x and y direction

On the XY plane in Fig.3-4 , that is, on the cross section, as for the horizontal X direction, the higher the velocity of fire, the greater the X, and as for the vertical Y direction, the lower the velocity of fire, the greater the Y.

#### 4. Presence of Bearing Clearance

If the bearing clearance exists, it must have some influence on the firing mode of the Gatling gun, as Fig.5

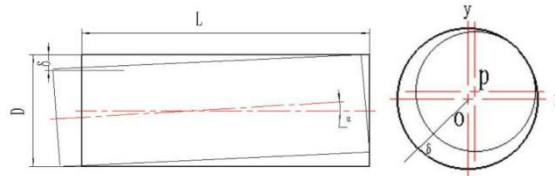


Fig. 5 Presence of Bearing Clearance

Viewing the  $\alpha$  angle at the bottom of the drawing of Fig.5, it can be seen as the delta height  $\delta$ , corresponding to the L length, so that the  $\alpha$  angle can be calculated:

$$\tan\alpha = \frac{\delta}{L} \tag{7}$$

According to Eq.(7) and Eq.(4)~(6), the center of gravity of the barrel group and bullet is:

$$\begin{aligned} x1 &= X + \delta\cos\alpha \\ y1 &= Y + \delta\sin\alpha \\ z1 &= Z \end{aligned} \tag{8}$$

In the calculation process of its  $x1, y1$  and  $z1$ , the  $\delta$  and the angle  $\alpha$  are involved, you can calculate the following, and the  $\delta$  is um and the  $x1, y1, z1$  is very close to the gapless  $xyz$ .

#### 5. Theoretical model

Depending on the hypothesis of the Bernoulli-Euler beam theory [2-3], the tube vibration function with moving force and moving mass was solved [4-8]. Therefore, two theories are used, and the first is the ballistic theory, the second is the unbalanced rotor theory.

The vertical deformation is represented by  $y$  and the longitudinal deformation is represented by  $x$ , as shown Fig.5, The vibration equation of the barrel considering the weight and acceleration of the projectile is:

$$\frac{\partial^2}{\partial Z^2} [EI(Z) \frac{\partial^2 y(Z,t)}{\partial Z^2}] + c_1 \frac{\partial y(Z,t)}{\partial t} + \rho(Z)A \frac{\partial^2 y(Z,t)}{\partial t^2} = (mS + F_2)\delta(Z - \xi) \tag{9}$$

$$\frac{\partial^2}{\partial Z^2} [EI(Z) \frac{\partial^2 x(Z,t)}{\partial Z^2}] + c_2 \frac{\partial x(Z,t)}{\partial t} + \rho(Z)A \frac{\partial^2 x(Z,t)}{\partial t^2} = (mg + F_1)\delta(Z - \xi) \tag{10}$$

$$S = \frac{\partial^2 Z}{\partial t^2} + 2v \frac{\partial^2 y}{\partial Z \partial t} + v^2 \frac{\partial^2 x}{\partial Z^2} \tag{11}$$

$$\xi = \int_0^t Z(t) dt \tag{12}$$

$$y_x = \sqrt{y_1^2 + x_2^2} \tag{13}$$

Where:  $E$  is the elastic modulus of the material;  $I^{(Z)}$  is the moment of inertia of the cross-section of a cage-like structure;  $c_1, c_2$  is the viscous damping coefficient;  $y$  is the vertical deformation of the axis;  $x$  is the longitudinal deformation;  $y_x$  is the resultant displacement.  $\rho^{(Z)}$  is the material density;  $A$  is the cross-sectional area of the barrel;  $I^{(Z)}$  and  $A$  are constants under the simplification of uniform section;  $m$  is the mass of the bullet;  $F$  is the axial force of barrel from muzzle to tail,  $v(t)$  is the moving speed of the bullet;  $g$  is the acceleration of gravity;  $\xi$  is the travel of the bullet from interior ballistic calculation;  $S$  is the additional term of an external force acting on the barrel after considering the inertial effect of the bullet, and  $\delta(\dots)$  is the Dirac function.

The bullet goes through an unbalanced force, under the action of the unbalanced force, the rotor will produce vibration. At high speed, even a small mass eccentricity will produce a larger centrifugal force. The data are obtained from their modeling, and some are obtained from relevant literature [11-12].

## 6. Case Analysis

### 6.1 Consider the deviation caused by clearance

A Gatling gun with clearance is shown in Fig.5. The mass of the rotor can only be taken from the barrel, gun machine, and other structures, and the mass that can rotate, in combination with [13] 0 groups of partitions (18 48), 3 groups of partitions (41 81), 4 groups of partitions (71 114), and 5 groups of partitions (105 160), and the unit is  $\mu m$ . The following maximum deflection angles can be obtained according to Eq.(7), as Table2

Table 2. Deflection caused by different clearances

Partition	0 group		3 group		4 group		5 group	
$\alpha$	11.4903	11.4876	11.488	11.4846	11.4855	11.4816	11.48	11.47

The drawn image is shown in Fig. 6:

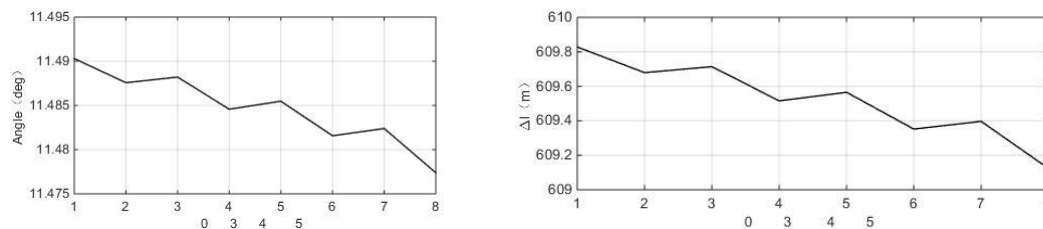


Fig. 6 Deviation caused by different clearances Fig. 7 Sideflight caused by bearing

The deviation during shooting can be used to calculate the impact point formed during the specific shooting of 3000m.

Assuming that the bullet is in plane flight, and there is no ballistic bending caused by the bullet's dead weight, the calculation of this point at 3000m will lead to the flight distance, as shown in Table 3, and the results are shown in Fig. 7:

$$\Delta l = 3000 \tan \alpha \tag{14}$$

Table. 3 Offset Distance Caused by Different Clearances

Partion	0 group		3 group		4 group		5 group	
$\Delta l$	609.82	609.679	609.71	609.51	609.56	609.35	609.39	609.124

For the type shown in formula (1), the increase of the deflection angle can reduce the range of the deflection angle, but the increase of the deflection angle will lead to the failure of mobility. The

size is mainly the layout of internal parts [14], of course, the smaller the better. Considering all kinds of situations, the change in the deflection angle is relatively small.

In the practical shooting mode, the deviation caused by the gap can be considered from the weapon shooting mode and can be compensated in the operation

## 7. Experiment

The M134 imitation was fired, with a tube length of 559mm and an initial velocity of 838m/s. It can be seen from Fig.6 that the dispersion of five bullets is relatively large, because when the rotational speed of the star body still reaches a stable rotational speed, it is fired. When the speed reaches a stable speed, the dispersion of bullets is relatively concentrated and 20 consecutive shots in 2000rpm and 4000rpm

From Fig. 6-7, it can be seen that at the 100m vertical target, the dispersion R100 of the bullets is about 50mm, and the included angle of dispersion is about 1mil. The bullets dispersion R50 is about 10mm, and the included angle of dispersion is about 0.2mil, indicating that the muzzle bounce is small and the firing stability is good when the rotary tube machine gun fires at a high frequency. And Fig.8 shows that 4000rpm target density is better than 2000rpm.

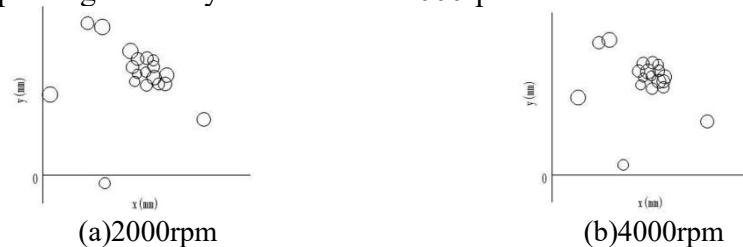


Fig. 8 100m vertical target density at 20 consecutive shots

The M134 imitation is very good, then it is not distribute of firearms at the 6.5 secret level at table 3, and the space is 100m.

## 8. Summary

(1)Clearances: According to the calculation of five clearances, the angle deviation is about 11.50, and based on the target of 3000 meters, the sideflight is about 600 meters.

(2)Surface killing: From the perspective of Gatling weapons, it has been officially determined that transfer weapons must primarily rely on surface killing.

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