Modeling and Simulation Analysis of Rigid-flexible Coupling Dynamics of Ramming Mechanism Based on Reissner-Mindlin's Medium-thick Plate Theory

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Abstract. In order to obtain the dynamic characteristics of a ramming mechanism, the multi-rigid-body and rigid-flexible coupling dynamic models were established in Recurdyn. Considering the structural characteristics of the link, the deformation motion of the link is described by using the Reissner-Mindlin plate theory, and the dynamic model of a bomb feeder is established considering the influence of non-ideal factors such as transmission clearance, friction and so on, the dynamic characteristics of a bullet-feeding machine are simulated and analyzed. Compared with the multi Rigid body dynamics model, the simulation results of the rigid flexible coupling model are more consistent with the experimental results, in addition to the polygon effect, other factors such as transmission gap and so on are also the causes of the fluctuation of the chain head speed of the ammunition conveyer. In addition, with the periodical movement of the Ammunition Conveyer, the wear between the pin holes of the connecting links will become more and more serious, and the closer you get to the end of the chain, the greater the trend.

1. Introduction

The difficulty of the automatic loading system is to transfer projectiles and propellants to the barrel at any angle [1]. In general, the study of the dynamic characteristics of the ramming mechanism mainly focuses on the dynamic model of the chain drive, the reliability of the action and the consistency of bayonet-chamber of gun [2-4]. There are three kinds of dynamic models for the chain drive of the ramming mechanism: uniform elastic band model, multi-rigid body model and rigid-flexible coupling model [5]. The multi-rigid-body model and the rigid-flexible coupling model of the trajectory chain can be applied to the dynamic model of the ramming mechanism. In the study of the multi-rigid-body model, Liu Taisu [6] and others established the normal contact force model and the plane contact force model respectively for different contact positions and contact modes. In this paper, a multi-rigid body dynamics model of open chain drive mechanism of a ramming mechanism is established, and the influence of clearance change between roller and sprocket slot on the kinematic accuracy and dynamic characteristics of the system is discussed. In the aspect of rigid-flexible coupling, Hao Chiyu, Yan Pengcheng and others [7] used Recurdyn to set up the dynamic model of a certain ramming mechanism. Then the flexible key parts are made in Recurdyn, which was used to analyzed and determined the position of the danger point. Compared with the previous studies on the dynamics of ramming mechanism, the rigid-flexible coupling model is less studied and the solid element is used to describe the deformation motion of components. This is of course related to the shape of the
component, but under the same premise of calculation accuracy, the problem of too much calculation is inevitable.

In this paper, the dynamic characteristics of the chain drive of the ramming mechanism are mainly studied. The rigid-flexible coupling dynamic model of the ramming mechanism is established by using the Reissner-Mindlin plate theory to describe the deformation motion of the link [8], which is compared with the multi-rigid body dynamics model and the experiment of ramming mechanism.

2. The Structure and Action Principle of the Ramming Mechanism
The ramming mechanism studied in this paper is mainly composed of conveying channel, transmission case, sprocket, chain and so on. The structure is shown in figure 1.

![Figure 1. Schematic diagram of the ramming mechanism.](image)

The chain is composed of a chain head, inner links, outer links, rollers and pins (not shown in the diagram). The inner link, the outer link and the rollers on both sides are connected by the pin shafts. The roller contacts the sprocket teeth and the rail groove of the conveying channel. When the ramming mechanism carries on the projectile delivery action, the chain is driven by the chain wheel to move toward the breech direction in the track, and the chain head pushes the projectile forward.

3. Rigid-flexible Coupling Dynamics Modeling Theory Based on Reissner-Mindlin Plate Theory

3.1. Rigid-flexible Coupling Control Equation for Reissner-Mindlin Plate
The rigid-flexible coupled motion diagram of R-M plate is shown in Figure 2. Assume that any point $c$ on the plate reaches point $c'$ after deformation, and the radius vector from point $c$ to $c'$ is $u$, that is, the deformation amount. The vector from the origin $O_G$ of the R-M plate coordinate system to the point $c$ is $\rho$, and the vector from origin $O_G$ of the inertial frame of reference to the point $c'$ is:

$$r_c = r_s + r_{sc}$$

where, $r_s$ is the radius vector from the origin $O_G$ of the inertial frame to the origin $O_s$ of the conjoined frame. $r_{sc}$ is radius vector from the origin $O_s$ of $O_s$ - $X_sY_sZ_s$ coordinate system to $c'$. It can be written:

$$r_{sc} = A_s (\rho_s + u_c)$$

where, $A_s$ is the direction cosine matrix of the coordinate system $O_s$ - $X_sY_sZ_s$ relative to the inertial frame of reference. The deformation $u_c$ can be described by modal coordinates:

$$u_c = \Phi_c q_f$$

where, $\Phi_c$ is the deformation modal matrix; $q_f$ is the generalized coordinates of the deformation.
Take the first-order derivative of equation (1) with respect to time, we can get:
\[ v_c = \dot{r}_c + \omega_s x r_w + \dot{r}_w \]  
where, \( \omega_s \) is the angular velocity of the coordinate system \( O_s - X_s Y_s Z_s \), the expression of \( \dot{r}_w \) is:
\[ \dot{r}_w = A_s \ddot{u}_s = A_s \Phi_s q_f \]  

Take the first-order derivative of equation (5) with respect to time, we can get:
\[ a_c = \ddot{q}_c + \omega_s \times (\omega_s \times r_w) + 2\omega_s \times r_w + \varepsilon_s \times r_w + \ddot{r}_w \]  
where, \( a_s \) and \( \varepsilon_s \) are acceleration and angular acceleration of \( O_s - X_s Y_s Z_s \) respectively. The expression of \( \dot{r}_w \) is:
\[ \dot{r}_w = A_s \ddot{u}_s = A_s \Phi_s \ddot{q}_f \]  

3.2. The Rigid-flexible Coupling Dynamic Equation of the Bullet-feeding Machine

The system is considered that a multibody system is composed of \( m \) rigid bodies and \( n \) flexible bodies. The mechanical hinges of interconnected rigid bodies and flexible bodies and the kinematic constraints of specific motion can be constructed by a set of nonlinear algebraic constraint equations. The constraint equation can be written in the following form:
\[ C(q_c, q'_c,..., q_n, q'_n, q_f, q'_f, t) = 0 \]  
where \( t \) is time, \( q_c \) for the generalized coordinate vector of the rigid body, \( q_f \) and the generalized coordinate vector of the flexible body.

According to the first kind of Lagrange equation, the dynamic equations of the system are obtained:
\[ \begin{bmatrix} m_r & m_f \\ \text{Symmetry} & m_f \end{bmatrix} \begin{bmatrix} \ddot{q}_c \\ \ddot{q}_f \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K_f \end{bmatrix} \begin{bmatrix} q_c \\ q_f \end{bmatrix} + \begin{bmatrix} C^{Tr}_{qq} \\ C^{Tr}_{qf} \end{bmatrix} \lambda = \begin{bmatrix} (Q_c)_c \\ (Q_f)_c \end{bmatrix} + \begin{bmatrix} (Q_c)_v \\ (Q_f)_v \end{bmatrix} \]  
where, \( m_r, m_f, m_f \) are the rigid body items, the rigid coupling items and the flexible body items of the mass matrix, respectively; \( K_f \) is stiffness matrix of the flexible body; \( C^{Tr}_{qq}, C^{Tr}_{qf} \) is constraint Jacoby matrix of the rigid body and the flexible body part, respectively; The \( \lambda \) is Lagrange multiplier vector; \( Q_c \) is generalized outer force vector, and the secondary \( Q_v \) velocity vector.

4. Comparison of Rigid-flexible Coupling Dynamic Modeling and Simulation Test of the Ramming Mechanism
4.1. Rigid-flexible Coupling Dynamic Modeling of the Ramming Mechanism

The solid model of the ramming mechanism was established by 3d modeling software, and then imported into the dynamic simulation software RecurDyn. After establishing the constraint and contact, the multi-rigid body dynamics model of the ramming mechanism is established.

A finite element model described by the R-M plate element of the link is generated by the ANSYS software, as shown in figure 3. The results of the modal analysis are shown in Table 1. The ”outer” refers to the outer link and the ”inner” to the inner link. In RecurDyn, the first 14 modes are selected to generate the flexible body file, and the reference point of the flexible body file is chosen as the center of mass. The rigid-flexible coupling dynamic model of the ramming mechanism in RecurDyn is shown in Figure 4, and the analysis flow chart is shown in Figure 5.

|     | $f_1$  | $f_2$  | $f_3$  | $f_4$  | $f_5$  | $f_6$  | $f_7$  |
|-----|--------|--------|--------|--------|--------|--------|--------|
| outer| 7505.6 | 11663  | 13496  | 15730  | 18512  | 20145  | 22190  |
| inner| 7966.4 | 12206  | 13505  | 15654  | 21415  | 22608  | 23241  |
|     | $f_8$  | $f_9$  | $f_{10}$ | $f_{11}$ | $f_{12}$ | $f_{13}$ | $f_{14}$ |
| outer| 22311  | 26254  | 26900  | 27681  | 27898  | 30023  | 32416  |
| inner| 25086  | 27076  | 30277  | 30634  | 32668  | 34455  | 35051  |
|     | $f_{15}$ | $f_{16}$ | $f_{17}$ | $f_{18}$ | $f_{19}$ | $f_{20}$ | $f_{21}$ |
| outer| 33405  | 35161  | 35167  | 35878  | 39695  | 40214  | 40480  |
| inner| 36363  | 38003  | 40209  | 42281  | 42786  | 43418  | 44283  |

Figure 3. Rigid-flexible coupled dynamics model of the ramming mechanism.

Figure 4. Rigid-flexible coupled dynamics model of the ramming mechanism.

4.2. Driver Addition

The power of the ramming mechanism comes from the hydraulic cylinder, which realizes the rotation of the sprocket through the gear box. Because this paper only studies the dynamic characteristics of the chain, it does not establish the simulation model of the hydraulic system, only takes the measured output force of the cylinder as the driving force input of the rigid-flexible coupling dynamic model. The cylinder pressure test is shown in Figure 6 and the input force curve is shown in Figure 7. The driving force is applied to the driving rack.
5. Simulation Analysis

5.1. Comparison of Simulation and Experiment

The angle of 45° and 75° is chosen to carry out the simulation calculation, and the sign of the simulation stop is that the projectile is in position. The simulation results are compared with the experimental results. The experimental data are collected from the angular displacement sensor of the driving sprocket as shown in Figure 8. The comparison results of time that indicates arrival of the projectile are shown in Table 2. Since the displacement of chain head cannot be measured directly, the displacement and velocity of chain head are obtained by calculating the angular displacement of driving sprocket. The comparison results are shown in Figures 9-12.

![Figure 8. Angle displacement sensor for sprocket.](image)

| Shot angle / (s) | Experimental value/s | Simulation values/s |
|-----------------|-----------------------|---------------------|
|                 | Mean                  | Interval            | Multi-rigid-body   | Rigid-flexible-coupling |
| 45              | 0.2437                | [0.236,0.25]        | 0.223              | 0.247 |
| 75              | 0.2308                | [0.23,0.232]        | 0.219              | 0.23  |

Due to the randomness of the dynamic parameters, loads and boundary conditions of the system, the arrival time of the projectile is stochastic. Therefore, the mean and test range are taken as reference values after many tests and compared with the simulation results. From Table 2, it can be concluded that the dispersion degree of the time is small, and the simulation value does not fall in the range of the test value.

Figures 9-10 shows a comparison of experimental data and simulation results at a 45° angle.
According to the displacement comparison figure, the total displacement of the chain is larger than that in the simulation. The reason is that the calculated value is larger than the actual value when the angular displacement of the chain head is directly multiplied by the pitch circle radius of the sprocket. The displacement comparison figure shows that the feeding chain head in the multi-rigid body dynamic model reached the end point earlier and the time of the chain head in the rigid-flexible coupling model reaching the terminal point is almost the same as that of the simulation. The velocity comparison figure shows that the simulated velocity curve of the multi-rigid body simulation is always above the experimental one and the simulation data of the rigid-flexible coupling dynamic model is a little earlier than the experimental data. From the velocity comparison between experiment and simulation of the rigid-flexible coupling dynamic model, the velocity trend and the maximum value of the chain are consistent with the simulation data, and the simulation results show that the time point of the maximum velocity is slightly earlier than that of the experiment. This phenomenon is consistent with the displacement contrast curve. In addition, the velocity curve obtained from the experiment is the result of data smoothing.

Figures 11-12 shows a comparison of experimental data and simulation results at a 75° angle.

At 75° firing angle, the simulation data and the experiment data have the same tendency as at 45° firing angle, which means that the chain head in the multi-rigid body dynamic model reaches the end first. The time of the chain head in the experiment reaching the terminal point is almost the same as that of the simulation of the rigid-flexible coupling dynamic model, and the actual time is slightly ahead. In addition, at 75° the time of projectile delivery is earlier than that at 45°, which is consistent with the experimental data. From the velocity comparison figure, the velocity curve of the rigid-flexible coupling dynamic model simulation at 75° is more similar than that at 45°.

Combining the dynamic model of multi-rigid body and the dynamic model of rigid-flexible coupling with the results of experimental analysis respectively, it can be seen that the simulation data
of the dynamic model of multi-rigid body system is not in good agreement with the experimental data. The simulation data of the rigid-flexible coupling dynamic model have a good agreement with the experimental data, which can describe the actual ammunition ramming process.

5.2. Analysis of Simulation Results of Rigid-flexible Coupling Dynamic Model

Based on the rigid-flexible coupling dynamic model of the ramming mechanism, the angle is 75° and the step length is 1e-4. According to the actual situation, the symbol of the completion is that the chain head goes to the end of the channel. After the simulation, the dynamic characteristics of the chain are analysed.

As shown in Figure 13, the velocity of sprocket pitch circle line is compared with the velocity of the chain head.

![Figure 13. Velocity comparison.](image)

![Figure 14. The constrained force between chain link.](image)

As can be seen in the figure, the tangential velocity of the sprocket pitch circle is always greater than the velocity of the feeding chain head, and the velocity of the sprocket is always fluctuating. It can be seen that the velocity fluctuation of the chain not only depends on the polygon effect, but also the change of transmission gap and load.

Figure 14 shows the constrained force of the end, middle and first sections of the chain. The First Section is close to the chain head. As can be seen from figure, with the chain link close to the chain head, the constrained force is the trend of increasing. In the actual process of ramming, pin hole connection is used between the outer link and the inter link and similar multiple collisions will occur between the pin shaft and the pinhole. These collisions will lead to wear between the pins and holes, which reduce the transmission accuracy and efficiency and increase the system burden. The closer it gets to the chain, the worse it gets.

![Figure 15. Contact force between the first chain link and the chain head.](image)
Figure 15 is the contact force curve between the first link and the chain head. As can be seen from the figure, the environment of high-speed and heavy-load, the transmission gap and the polygonal effect of the chain lead to many times of contact and collision between the first link and the chain head, which results in a large impact load. Such a large impact load will aggravate the wear condition between the first link and the chain head, thus affecting the delivery process, which may lead to movement failure after long-term operation.

6. Conclusions
In this paper, the dynamic model of the ramming process is established by using RecurDyn software and the dynamic characteristics of the feeding process are analyzed. The conclusions are as follows:

- Compared with the multi-rigid body dynamics model, the rigid-flexible coupling dynamic model is more consistent with the experimental results, which shows that it is necessary to consider the flexible effect in the modeling process of the ramming mechanism.
- The example of 75° angle projectile transport shows that the factors that cause the velocity fluctuation of the projectile transport chain are not only polygon effect, but also transmission gap and load variation.
- The analysis of constrained force of chain link and contact force of chain link shows that there is a short time changing impact load between the outer link and the inter link, between head and chain link. The closer to the chain, the greater the impact load is.

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