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Modeling of Recoil Motion of Heavy Weapons with Hydropneumatic Recoil Mechanism

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Abstract: ***In this study, the recoil movement of heavy weapons with hydropneumatic recoil mechanism is modeled. The primary purpose of the study is to obtain the equation of motion of the recoiling parts in the weapon systems. For this purpose, the forces acting on the recoiling parts were determined, and the effects of each force were examined. Breech force is calculated via LeDuc equations for in bore period and verified by comparing with experimental studies. The breech force which is generated during the discharge of the remaining gases after the projectile leaves the barrel is also calculated and the total recoil force is obtained. Recoil motion caused by breech force is retarded by hydraulic brake and recuperator force in the recoil mechanism and friction. After determining breech and net retarding forces, the equation of motion is solved in MATLAB and the recoil distance is obtained. Calculated recoil distance, breech force and projectile velocity values are compared with test data and model is validated.***

Keywords: hydropneumatic recoil mechanism; heavy weapons; modeling

1. Introduction

When a round is fired, extremely high interior ballistic forces is formed inside the barrel due to the burning propellant. While these high forces accelerate the projectile towards muzzle, they also act on the breech and push barrel and some other components backward. Recoil mechanisms are used to dissipate most of the recoil energy which is formed in a very short time and store some of this energy to return the weapon system back to in battery position.

Different methods such as analytical, numerical and experimental have been implemented for modeling of recoil mechanisms in literature. Tiwari et al. [1] has improved a rigid body dynamics model and an experimental setup to investigate the effect of recuperator stiffness, recoil damping, tire stiffness and friction coefficient on recoil displacement. It is induced from the study that increasing recoil damping coefficient is the most effective way of decreasing recoil displacement. Hajihosseinloo et al. [2] has investigated the performance of high energy gun recoil absorbers. An experimental setup that simulates gun reaction loads is prepared for measurements and a theoretical model which predicts recoil velocity and buffer pressure is built for calculations. It is explained in their study that discharge coefficient is very important for the buffer performance. Hassaan [3] has investigated recoil mechanisms of cannons which have air springs and hydraulic damper with constant damping coefficient. A nonlinear barrel assembly model is built and solved via Runge-Kutta 4 method. It is revealed from his study that maximum barrel displacement and barrel settling time decreases with increasing the number of air springs. Hassaan [4] has also studied recoil mechanism of 155 mm howitzer which has a hydraulic damper with nonlinear damping characteristic and helical spring with constant stiffness. Dynamic response of the barrel assembly to firing is investigated by using extremely nonlinear model for different firing angles. It is understood from his study that increasing the firing angles increases maximum displacement and settling time of the barrel assembly. Zaloğlu [5] has performed a comprehensive finite element based analysis of recoil springs in automatic weapons which includes effects of all important parameters such as nonlinear force deflection characteristics, dynamic stress etc. In addition, an experimental study is carried out to validate the results from analysis. Yang [6] has studied on optimization of recoil mechanism via dynamic simulation analysis. Small volume, high efficiency and low cost are considered as optimization parameters for the vehicular integration of artillery weapons. It can be inferred from the study that maximum recoil distance can be limited within a certain value by controlling the orifice area. Elaldı and Akçay [7] has developed a model to predict important parameters of the recoil mechanism by using method of Runge-Kutta. A hydropneumatic recoil mechanism is designed, produced and tested for 155 mm weapon system. Oil pressure, hydraulic brake force and recoil length are measured via experimental setup and compared with the predicted values from model. Lin et al. [8] have studied on dynamics of the recoil mechanism of 155 mm self-propelled howitzer and they have obtained recoil length, velocity and acceleration. To find the required force, free body analysis is applied on the system component firstly and experience data and curve fitting methods are also applied together for more complex systems. Additionally, the maximum recoil distance that is aimed to be minimized is specified as cost function of the optimization procedure.

In this study, the modeling of hydropneumatic recoil mechanisms used in 105 mm howitzers has been carried out. The magnitudes of the breech force and net retarding force which is sum of hydraulic brake, recuperator force and frictional forces are calculated from the model. In addition, position, velocity and acceleration values of the recoiling parts were also obtained. The mathematical model was verified by comparing some of these values with the data obtained from firing tests. Studies in recent years have focused on decreasing the weight of weapon systems to improve mobility. This change in weight necessitates to make some modification in design of recoil mechanisms. The model that is validated in this study can be used to define what kind of change is necessary in which parameters.

2. Mathematical Modelling

The mathematical model of the recoil motion is the equation of motion of the recoiling parts. The equation of motion can be obtained by using one degree of freedom model shown in Figure 1.

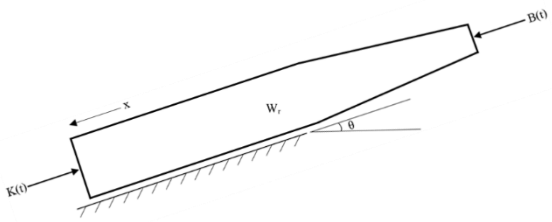

Figure 1: One degree of freedom model

The equation of motion for the recoiling parts can be expressed as follows.

$$m_r \ddot{x} = B(t) - K(t) + W_r \sin\theta \quad (1)$$

$B(t)$ and $K(t)$ represent the breech force and net retarding force respectively, and W_r represents the weight of the recoiling parts.

2.1 Breech Force

The breech force was calculated for two time periods: the time until the projectile leaves the barrel and the time until the propellant gases go out to the atmosphere after the projectile leaves the barrel.

2.1.1. In Bore Period

In order to calculate the breech force, the relationship between the breech force and the projectile travel in the barrel should be established. Then, changes of breech force, projectile velocity and position with time are obtained. These calculations are made with the help of LeDuc equation which is an empirical equation [9].

$$v' = \frac{a\,u}{b+u}, \quad (2)$$

Where, v' is in-bore velocity of projectile, u is projectile travel in bore, a and b are model parameters. Model parameters and terms used in calculating these parameters are given below.

$$a = v_0'(Q+1) \quad (3)$$

$$b = QU_0 \quad (4)$$

$$Q = \left(\frac{27}{16}\frac{P_M}{P_e} - 1\right) - \sqrt{\left(\frac{27}{16}\frac{P_M}{P_e} - 1\right)^2 - 1} \quad (5)$$

$$\frac{P_M}{P_e} = \frac{2gU_0 P_M A}{v_0'^2\left(W_p + \frac{W_c}{2}\right)} \quad (6)$$

Where, v_0' is muzzle velocity of projectile, U_0 is tube length, P_M is peak chamber pressure, P_e is mean chamber pressure, A is bore area, W_p is weight of projectile and W_c is weight of propellant charge. Projectile velocity can be calculated by substituting the values of a and b into Eq. 2.

$$v' = \frac{v_0'(Q+1)u}{QU_0 + u} \quad (7)$$

The expression that gives the relationship between the breech force and the projectile travel is given below [10, 11].

$$B = \left(\frac{W_p + \frac{W_c}{2}}{g}\right)\left[\frac{a^2 bu}{(b+u)^3}\right] \quad (8)$$

When the necessary arrangements are made, the equation that gives the breech force through projectile travel in the barrel is obtained.

$$B = \left[\frac{\left(W_p + \frac{W_c}{2}\right)v_0'^2 (Q+1)^2}{g}\right]\left[\frac{QU_0 u}{(QU_0 + u)^3}\right], \quad (9)$$

Similarly, the equation that gives the relationship between projectile travel and time can be found by using the LeDuc equation.

$$v' = \frac{du}{dt} = \frac{a\,u}{b+u} \quad (10)$$

$$dt = \left(\frac{b+u}{au}\right)du \quad (11)$$

By integrating the equation above and using $u = U_0$ for $t = t_0$ as the boundary condition, the time dependent projectile travel is obtained as follows.

$$t = t_0 - \left[\frac{b}{a}\ln\left(\frac{U_0}{u}\right) + \frac{U_0 - u}{a}\right] = t_0 - \frac{QU_0 \ln\left(\frac{U_0}{u}\right) + (U_0 - u)}{v_0'(Q+1)} \quad (12)$$

The change of breech and projectile velocity through projectile travel and time can be obtained by using Eq.7, Eq.9 and Eq.12.

2.1.2. Gas Ejection Period

After the projectile leaves the barrel, the pressure and velocity of the gases inside the barrel are still quite high and therefore should be included in the calculations when determining the total breech force. The pressure at projectile exit and the time passed in bore period are used as input to the breech force calculations during the gas ejection period. The breech force in the gas ejection period can be calculated from the following equations [9].

$$B = P_b A \quad (13)$$

$$P_b = P_0\left(1 + \frac{t - t_0}{\phi}\right)^{2\gamma/(1-\gamma)} \quad (14)$$

When the above equations are combined, the equation that gives the breech force in gas ejection period is obtained.

$$B = P_0 A\left(1 + \frac{t - t_0}{\phi}\right)^{2\gamma/(1-\gamma)} \quad (15)$$

P_b refers to the pressure in the barrel during gas ejection period, P_0 is the breech pressure at projectile exit, t_0 is the time until the projectile leaves the barrel, ϕ is the duration of the gas ejection period, γ is the rate of specific heats.

2.2 Net Retarding Force

There are three main forces that contribute the net retarding force and these forces are recuperator force, frictional force and hydraulic brake force. Additionally, there are several assumptions that are made during net retarding force calculations and these are:

- Compression and expansion processes of the gas inside recuperator cylinder are adiabatic and gas is ideal.
- Coefficient of friction is constant.
- Flow inside hydraulic cylinder is quasi-steady, incompressible, inviscid and one directional.

2.2.1. Frictional Force

Frictional force occurs when recoiling parts slides on cradle during recoil motion and that force should be included to net retarding force. Frictional force can be obtained from the equation below.

$$F_f = \mu W_r \cos\theta \quad (16)$$

2.2.2. Recuperator Force

The main purpose of the gas inside the recuperator cylinder is to store energy during recoil and bring the weapon system back in battery position by using this stored energy. The force that is formed during recoil by compression of gas is called recuperator force and contributes to net retarding force against recoil motion. Compression and expansion processes of the gas are assumed polytropic and recuperator force can be calculated from equation below.

$$P\,V^{n} = constant \qquad (17)$$

Where, P is gas pressure, V is gas volume and n is ratio of specific heats. If it is assumed that i and x represent the values in-battery position and at any recoil distance respectively, the following equations can be established.

$$\mathrm{P_i V_i^n} = \mathrm{P_x V_x^n} \qquad (18)$$

$$P_x = P_i (V_i / V_x)^n \qquad (19)$$

$$V_x = V_i - \Delta V_x = V_i - A_R x_r \qquad (20)$$

By making some arrangements in the equations above, the equation that gives recuperator force is obtained.

$$\mathrm{K_a} = \mathrm{A_R P_x} = \mathrm{A_R P_i} . \left(\frac{\mathrm{V_i}}{\mathrm{V_i - A_R x_r}}\right)^{1.4} \qquad (21)$$

Where, A_R is the cross-sectional area of the pneumatic cylinder and x_r is the recoil distance

2.2.3. Hydraulic Brake Force

During recoil, hydraulic fluid is forced to flow through orifices by piston inside the hydraulic cylinder. While piston moves, hydraulic fluid causes a resistance to this motion and this resistive force is called hydraulic brake force. This force is calculated from the pressure difference between two sides of the effective piston area [9].

$$F_0 = (P_h - P_l) A_p = \Delta P\; A_p \qquad (22)$$

Where, P_h is pressure in high pressure chamber, P_l is pressure in low pressure chamber and A_p is effective area of the piston. Pressure difference between high and low pressure chambers are calculated from the equation below:

$$\Delta \mathrm{P} = \frac{\mathrm{A^2 v^2 \rho}}{\mathrm{2 C_0^2 a_0^2}} \qquad (23)$$

Where, A is cross section area of cylinder, v is velocity of piston or in other words velocity of recoil, ρ is fluid density, C_0 is orifice discharge coefficient and a_0 is average area of orifice. Substitute Eq. 23 into Eq. 22 gives the equation for hydraulic brake force.

$$F_0 = \frac{A^2 v^2 (x) \rho A_p}{2 C_0^2 a_0^2} \qquad (24)$$

Net retarding force equals the summation of frictional force (Eq. 16), recuperator force (Eq. 21) and hydraulic brake force (Eq. 24).

$$K = \mu W_r \cos\theta + A_R P_0 . \left(\frac{V_0}{V_0 - A_R x_r}\right)^{1.4} + \left(\frac{A^2 v^2 (x) \rho A_p}{2 C_0^2 a_0^2}\right) \qquad (25)$$

$$m\ddot{x} = B(t) + W_r \sin\theta - \mu W_r \cos\theta - A_R P_0 . \left(\frac{V_0}{V_0 - A_R x_r}\right)^{1.4} - \left(\frac{A^2 v^2 (x) \rho A_h}{2 C_0^2 a_0^2}\right) \qquad (26)$$

3. Results

In this study, equation of motion is solved, and results are compared with the data obtained from firing tests. 105 mm howitzer that is produced by Mechanical and Chemical Industry Company Heavy Weapons and Steel Factory is used for both solution of the model and firing tests. In addition, Nexter ammunition is used for both calculations of breech force caused by pressure inside the barrel and firing tests.

3.1 Breech Force

Breech force vs recoil travel data obtained from mathematical model and firing tests is given in Figure 2. Maximum breech force is measured and calculated about 3.5 MN from experiments and model respectively. It seems from the figure that model results and test data are very close to each other. It can be said that the model is verified for breech force change during projectile travel by firing tests.

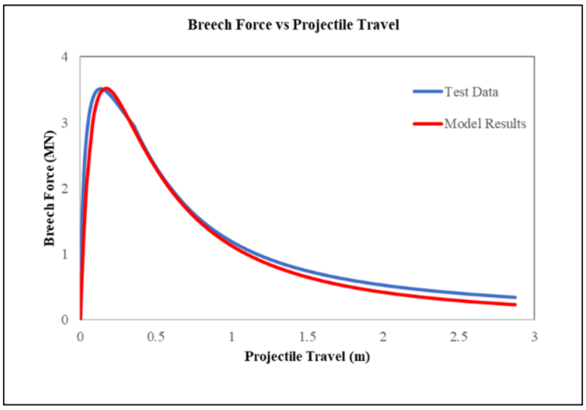

Figure 2: Breech force vs projectile travel

3.2. Velocity of Projectile

Comparison of model results and firing test data for 105 mm howitzer is given in Figure 3. Muzzle velocity is calculated from the model as 680 m/s and is measured from firing test as 695 m/s. The difference between these values is about 2 % and calculated results from the model and measured data from firing tests are very close to each other. It is understood from Figure 3 that the model is verified for velocity of projectile change during projectile travel by firing tests for 105 mm howitzer.

Additionally, change in velocity of projectile is compatible with change in breech force. It increases with higher acceleration where the breech force is very high, and it increases with lower acceleration where the breech force has low values.

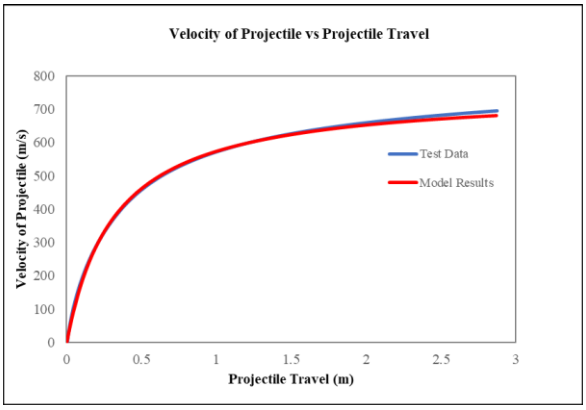

Figure 3: Projectile velocity vs projectile travel

3.3. Recoil Distance

35 firings were made in firing tests and maximum recoil distance is measured for 300 mils and 1150 mils firing angle values. Average of maximum recoil distance is 1135 mm and 766.7 mm for 300 mils and 1150 mils respectively. Additionally, maximum recoil distance change with time is calculated from the model and results are given in Figure 4. Maximum recoil distance is calculated as 1109 mm and 746 mm for 300 mils and 1150 mils respectively. Model results and test data are compatible with each other and difference between them is about 2.5 %.

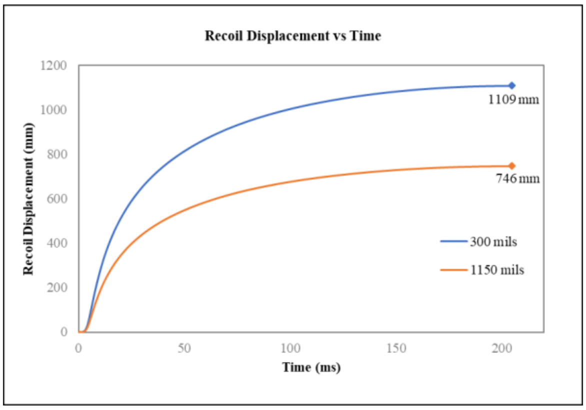

Figure 4: Recoil distance vs time

3.4. Recoil Velocity and Acceleration

Recoil velocity and acceleration were calculated from the model that is validated by breech force, velocity of projectile and recoil distance values from firing tests. Results that are calculated for two different firing angles are given in Figure 5 and Figure 6. It is seen from the figures that recoil velocity and acceleration increase where the breech force increased from zero to its peak value rapidly. After that acceleration decreases due to that net retarding forces starts to overcome breech force and then it reaches minus values which means recoiling parts begins to slow down. Peak recoil velocity and acceleration values are calculated as 44.9 m/s and 21.4 m/s^2 for 300 mils and 30.3 m/s and 14.5 m/s^2 for 1150 mils.

Additionally, it can be said that recoil mechanism does its duty successfully which is dissipating recoil energy that is formed in very short duration by extremely high internal ballistic forces.

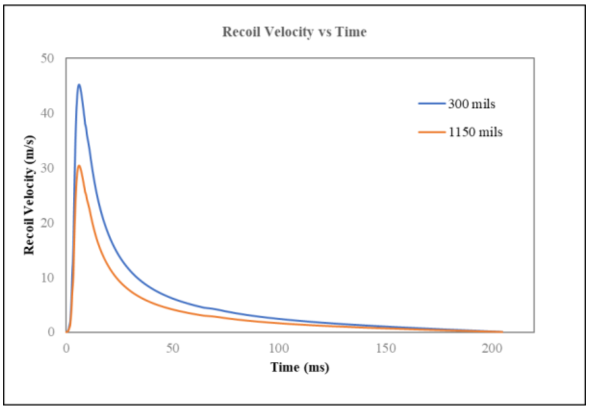

Figure 5: Recoil velocity vs time

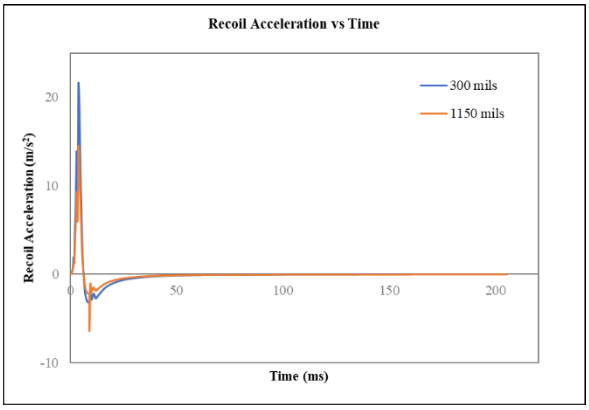

Figure 6: Recoil acceleration vs time

4. Discussion

In this study, the recoil movement of heavy weapons with hydropneumatic recoil mechanism is modeled. Equation of motion for recoiling parts was formed after obtaining breech force and net retarding force. Results that calculated from model were given in graphics and the model is validated via comparison of model results and data from firing tests.

Firstly, breech force is calculated through projectile travel in barrel from the model. Breech force was increased rapidly as expected due to high internal ballistic pressure and after reaching to its peak value, it decreased in a much longer period. Results from model and measured data from firing tests were close to each other and that means model works properly.

Secondly, projectile velocity change through barrel is calculated from the model. Projectile velocity is increased with high acceleration right after firing and continue to increase with lower acceleration due to decrease in internal pressure inside the barrel. It is inferred that the model is verified for in-bore period once again since difference between measured data and test data is about 2 %.

Thirdly, to verify model including both in bore period and gas ejection period, recoil distance change with time is calculated for two different firing angles. It is proven that model results are close to real data by comparing calculated maximum recoil distance and results from firing tests that difference between them is about % 2.5.

After model is validated velocity and acceleration change of recoiling parts wit time is calculated. Results show that recoil mechanism does its duty successfully which is dissipating recoil energy that is formed in very short duration by extremely high internal ballistic forces.

The mathematical model that is built in this study helps designers and contributes especially preliminary design phase of recoil mechanisms for new weapon systems. This kind of modeling can assist designers to predict maximum recoil distance or determine some critical parameters to stop recoiling parts in a specified recoil distance. In addition, it can be said that model is used to define required design changes of an existing recoil mechanism due to the weight changes in the weapon systems.

5. Conflicts of Interest

The authors declare no conflict of interest.

6. Funding

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7. Acknowledgments

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