國立交通大學

機械工程學系

碩士論文

制退復進機之動態模擬分析與最佳化

Dynamic Simulation Analysis and Optimization of Recoil Mechanisms

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摘要

制退復進機的主要功能是用於吸收火炮射擊時所產生的後座力，並且利用壓縮氣體或彈簧將砲管回復至射擊前的位置。換言之，制退運動是火砲在射擊時，彈頭因氣體作用而向前發射，另外部分氣體作用於燃燒室而使機構向後移動，且制退完成後，砲管與其連接部份會恢復至擊發狀態。近幾年來，制退復進機的發展趨勢專注在車載系統之整合上。因此，短制退行程、高制退效率與低成本制退復進機的需求，漸漸受到重視。

本論文針對減少制退復進機的制退距離，提出了一個動態模擬分析的模型。在動態模型的建立上，主要是建立制退復進機、砲管與支撐結構。而針對所建立出的動態模型的特性，設計一目標函數並介紹所使用的設計參數。此外，藉由最佳化原理分析其目標函數及所考慮的設計參數，使射擊時制退復進機的制退距離有更符合設計需求的表現。最後，分析制退距離與控制孔面積的關係，提出藉由控制孔的概念，使制退復進機在限定的制退距離內停止。

Dynamic Simulation Analysis and Optimization of Recoil Mechanism

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ABSTRACT

The recoil mechanism is mainly used to absorb the recoil force during firing, and furthermore it can use compressed gas or springs to return the gun tube to its original position for artillery weapons. In other words, the recoil motion is the rearward movement of the gun during and after firing. The recoil motion is caused by the reaction of the projectile and the propellant gases. After recoil, the gun and connecting parts return to the original firing position. In recent years, the development trends of artillery weapons with recoil mechanisms focus on the vehicular integration. Therefore, a small volume, high recoil efficiency, and low cost of recoil mechanism are necessary.

This thesis presents dynamic analysis and simulation on recoil mechanism, which is used to reduce the recoil length of the recoil mechanism. The first objective is to create a dynamic model of the recoil system, which includes the recoil mechanism, the barrel, and supporting parts. The second objective uses the created dynamic model to design an objective function for the recoil mechanism, some design parameters are introduced here. The third objective is the optimization; some parameters of the recoil mechanism are optimized to give a better result on the recoil length of the device. Finally, the relation

between the recoil length and the orifice area is analyzed. The recoil mechanism can be stopped at a limit recoil length by controlling the orifice area.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATIONS

A	effective area of the recoil piston
A_1	contact area of packing on cylinder wall
A_b	bore area
A_c	cross-section area of the control rod
A_{cr}	effective area of the recuperating piston
A_R	effective area of the recuperating cylinder
B	breech force or gas force at the breech
$\overline{B}$	average breech force
$B(t)$	breech force or gas force at the breech
C_o	orifice coefficient
C_P	constant pressure specific heat
C_V	constant volume specific heat
$D(t)$	recoil impulse of time
$\sum F$	total force on the recoil mechanism
F_a	inertia force of recoiling parts
F_o	radial force of packing on cylinder
F_P	gas force at the base of the projectile

F_R recuperator force

H hydraulic braking force

$H(t)$ total resistant impulse of time

I^* total impulse

I_B^* impulse of the recoil force

K total braking force

K_p pressure factor

K_R rod pull force

$K(t)$ recoil braking force

L recoil distance

M_r recoil mass

N_1 guide force

N_2 guide force

P recoil pressure

P_a axial pressure in packing

P_b pressure in recoil cylinder

P_g gas preesure

P_i	recuperator gas pressure in battery
P_m	maximum fluid pressure
$P_{\max}$	maximum bore pressure
P_o	fluid pressure on packing at any recoil position
P_R	radial pressure in packing
P_{rx}	gas pressure at any position of recoil
$\Delta P(x)$	pressure drop across recoil orifice
Q_r	rate of flow
P_x	recuperator gas pressure at x
R	frictional force
R_c	packing friction of the recoil brake
R_P	packing friction
R_r	packing friction of the recuperator
R_{SL}	sliding track friction
U_0	barrel length
V	projectile velocity
V_g	gas volume
V_i	recuperator gas volume in battery

V_0	muzzle velocity of the projectile
V_x	recuperator gas volume at x
ΔV_x	increase in V_x
W_C	charge weight force
W_P	projectile weight force
W_r	weight of recoiling parts
X	recoil length
$\dot{X}$	recoil velocity
$\ddot{X}$	recoil acceleration
X_R	displacement of the control rod
a_e	effective area of orifice area
a_o	orifice area
a_R	braking retardation
g	acceleration of gravity
$h(x)$	velocity head at x position
m_R	recoil mass
n	polytropic exponent
s	absolute displacement of the gun body

t_b projectile transit time

t_r time of recoil stroke

u projectile travel

v absolute velocity of the gun body

v_0 recoil velocity of the gun body when the projectile exits the muzzle

$v(x)$ recoil velocity

$v_o(x)$ velocity of flow through orifice

x absolute displacement of projectile

θ elevation

$\alpha(t)$ centroid of the area

$\beta(t)$ centroid of the area

μ frictional coefficient

ν leakage factor

ω density of fluid

CHAPTER 1

INTRODUCTION

1.1 Background

Owing to the advancement of military views and scientific techniques, all countries in the world do their best to develop the war industry. One of the most important things is the development of guns, which are the backbone of the ground protection. However, gun protection is still insufficient for air attack because the airplane performance goes better and the developments of the air-to-ground weapon grow up day after day. Hence, artillery weapons, as shown in Figure 1.1-1, become the important ground firepower on the modern battlefield.

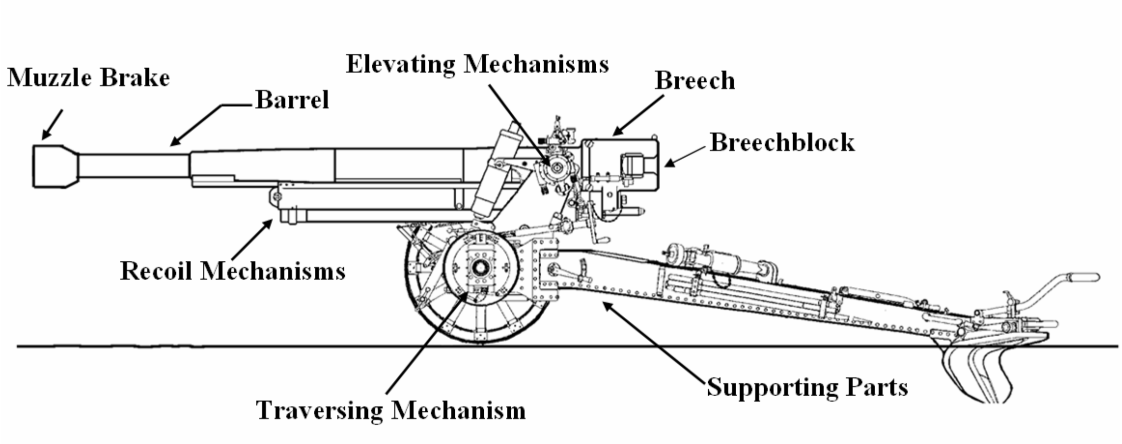


Figure 1.1-1 Artillery structure

The artillery weapons have been developed from the thirteenth century to the present. Generally, it includes a gun body and a gun mount. The gun body consists of a barrel, a breech, a breechblock, and a muzzle brake. In addition, the gun mount is composed of recoil mechanisms, elevating mechanisms, traversing mechanisms, and supporting parts. Among these parts, the muzzle brake and recoil mechanism can reduce the mass recoil force during firing, and push the gun body back to the original position after firing.

Before the mid-nineteenth century, general guns didn't assemble any device having the cushioning effect. For this reason, people had to design bulky guns to avoid the powerful recoil force. But the design led to a terrible mobility. It took much time to return the gun tube to original position and aim again. In order to solve above problems, the designers tried to install a buffer in the base which could generate a retarding force to stop the recoil motion. Finally, the recoil mechanism was created until the ninth decade of the nineteenth century.

Because the recoil mechanism was invented, the gun performance got unprecedented improvement. Therefore, the nineteenth century is a milepost in the developed history of artillery weapons. In recent years, the development trends of artillery weapons with recoil mechanisms focus on the vehicular integration. It can increase the mobility of artillery weapons. Therefore, a small volume, high recoil efficiency, and low cost of the recoil mechanism which can be easily installed on vehicles is very important.

1.2 Recoil Mechanism

The recoil mechanism, shown in Figure 1.2-1, is mainly used to absorb the recoil force during firing, and furthermore it can make use of compressed gas or spring to return the gun tube to its original position. In other words, the recoil is the rearward movement of the gun and connected parts during and after firing. It is caused by the reaction to the forward motion of the projectile and propellant gases. After recoil, the gun and connecting parts return to the in-battery, or firing position. This forward movement is called "counter recoil."

If the gun were mounted rigidly, without any recoil system, it would be practically impossible to build a carriage to withstand the load imposed upon it without rupturing, overturning, or moving. To bring the carriage stresses down to a reasonable value and to ensure the stability, a recoil system is interposed between the gun and the carriage. The recoil mechanism absorbs the energy of the recoiling parts over a certain convenient length and returns the gun to battery for further firing. The recoiling parts are the recoil mechanism and carriage that move with the gun in recoil and counter recoil.

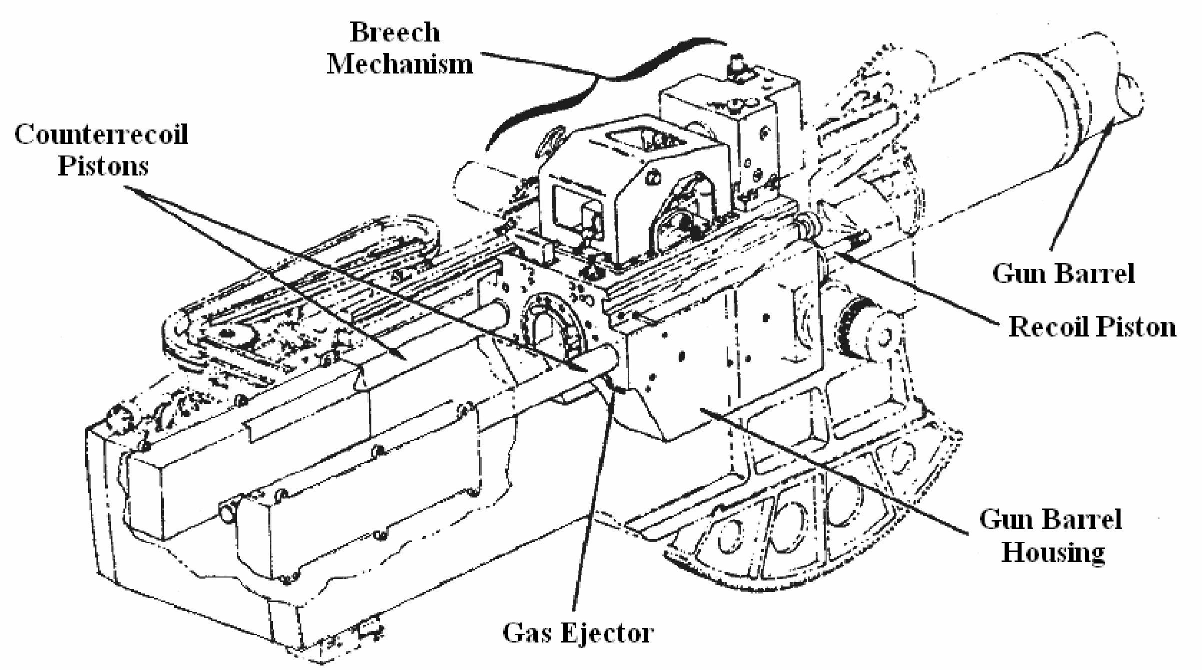


Figure 1.2-1 Recoil mechanism [1]

A recoil mechanism usually consists of two components as shown in Figure 1.2-2:

(1) Recoil brake – Normally, a recoil system consists of two stationary pistons attached to the slide of the liquid-filled cylinder in the housing. As the housing moves backward during recoil, the trapped liquid is forced around the piston head through metered orifices, slowing the movement of the housing.

(2) Counterrecoil mechanism – The counterrecoil mechanism consists of a piston set

in a pressurized cylinder. As the gun recoils, the piston protrudes further into the cylinder. After the end of the recoil period, the nitrogen gas pressure acting on the piston pushes the housing back into the original position. The piston may be attached to the slide or set in a chamber.

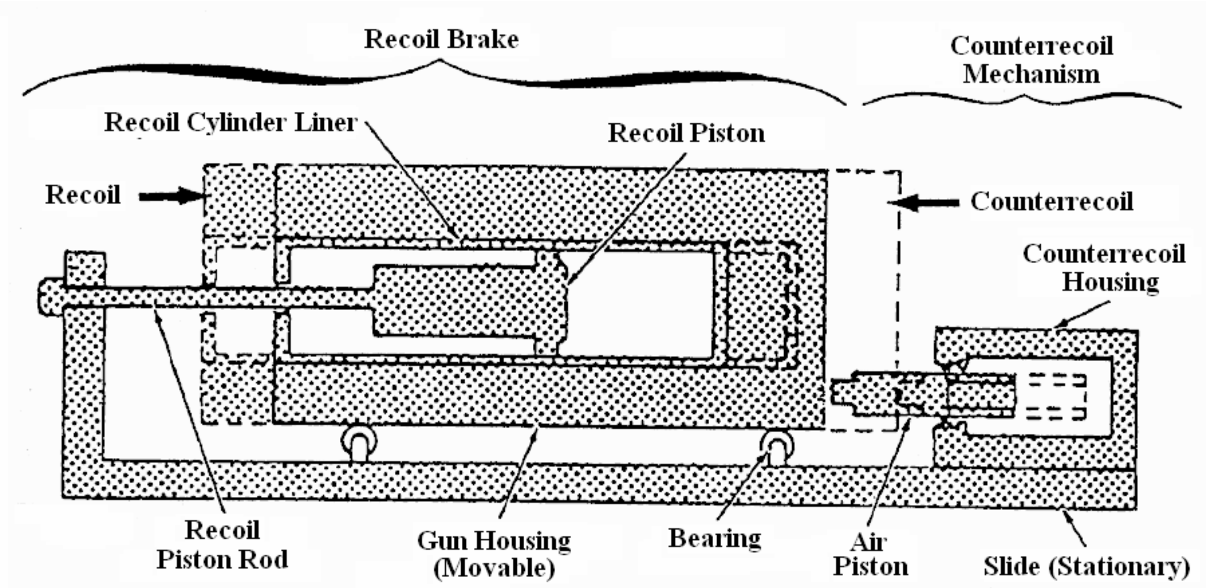


Figure 1.2-2 Recoil and counterrecoil system [2]

Besides, the recoil and counterrecoil system, shown in Figure 1.2-1, comprises two recoil cylinders connected hydraulically to a recuperator, and performs five functions:

(1) To absorbs the gun recoil force in prescribed recoil lengths.

(2) To maintain a nearly constant recoil force throughout the recoil stroke.

(3) To store energy to return the gun to the battery.

(4) To regulate the counterrecoil stroke to keep it within the prescribed rate-of-fire limits.

(5) To brake recoil and counterrecoil movement at the end of their strokes

The recuperator is a hydropneumatic device having separate chambers for hydraulic fluid and nitrogen gas. During the recoil stroke, the energy developed by the recoiling gun is absorbed by the recuperator and the recoil cylinder. The energy absorbed by the recuperator is stored as the compressed nitrogen gas. The energy absorbed by the recoil cylinders is dissipated by resistance to the flow of hydraulic fluid through throttling grooves between the stationary and moving parts of the cylinders.

During counterrecoil, the energy (gas pressure) provides the gun moving from its maximum recoil position to the original position. In this phase of counterrecoil, the recoil cylinders act as stroke regulators and release energy stored by the recuperator at a regulated rate.

To achieve the purpose of the recoil brake, there are many kinds of recoil mechanism, such as hydropneumatic and hydrospring. Moreover, the technical literatures are confidential in the foreign companies. Also, it is not easy to get the related technical data except from papers and patents. For this reason, this study will focus the literature review in US patents and Chinese papers from Mainland China to support the results of simulation. Other available will be explained in the following sections.

1.3 Motivations

The recoil mechanism is mainly used to absorb the recoil force during firing, and return the gun tube to its original position. The device, which plays a decisive role in the artillery weapons, is like a human heart. Because of the invention from the ninth decade of century, the performance of guns was improved, and the shooting velocity was increased greatly. Thereby, the device truly deserves to be studied.

However, most inventions and patent rights are owned by foreign companies, such as

Rheinmetall GmbH (Germany), Giat Industries (France), and Bofors Defence AB (Sweden). This technology relates to the national defense, therefore the developed countries will not ignore it when our country begins to develop it. By comparison, the defense industry in our country is with plagiary, and directly purchases weapons from foreign companies. It shows that the knowledge and techniques are insufficient. Fortunately, there are more and more resources available on the recoil mechanism.

The innovation of the recoil mechanism is not easy because there are so many problems which need to be solved. People usually design a new concept by searching patents, marketing research, or some innovative methods. But there is an important subject that the complete definition of the original problem about the recoil force during firing is required. If the definition is not clear, it is difficult to solve related problems and perform further analysis.

According to the above reasons, the purpose of this research is to find a mathematical model for the recoil force during firing. In addition, it can be implemented by the computer program for simulation. The results which are presented and constructed by this thesis can provide a clear understanding for designing the mechanism or improving the performance of recoil ability in the future.

1.4 Literature Reviews

The system of the recoil mechanism consists of eleven components: recoil piston rod, recoil piston, cushion, dish spring, recoil cylinder, recuperating cylinder, counterrecoil buffer, floating piston, recoil throttling valve, regulator, and regulator valve [3]. The general functions are introduced in Chapter 2. Because the recoil mechanism was developing for a long time, there are many available devices using in different kinds of guns. There is a general classification, hydrospring and hydropneumatic type. The classification of the recoil mechanism is often seen in the national defense industry. Theses are two main types of the recoil mechanism. These two types of the recoil mechanism principally differ from their action components, one is the spring and the other is compressed gas. Generally speaking, recuperator was originally with the spring type [3] [4].

Besides, the more important part is the forces and procedures of the recoil mechanism during firing. A high gas pressure, which acts on the base of the projectile and accelerates it forward, arises in the combustion chamber of the tube. The same gas pressure also acts on the breechblock of the tube, which is forced to the rear with a gas recoil force, which is also called the breech force. It lets the gun tube accelerate back, and the gun tube will be stopped by various braking components. After the recoil motion is completed, the recuperating mechanism returns the gun tube to its original position. Therefore, at the end of counterrecoil, the gun gets no moving forward, and the recoil part is braked hydraulically at the end of counterrecoil by means of the recoil brake. The period which recoil force acts is from the projectile firing to the mechanism stopping. Therefore, this period is a complete cycle during firing [5] [6].

1.5 Thesis Outlines

In order to find the recoil force situation during firing, the force analysis and the mathematical model will be constructed based on Simulink® in this thesis. Simulink® is one of the packages in Matlab®. Furthermore, the model can help to realize the designs on the available products and literature, especially on the mechanism with some parameters. The brief description and outlines in this thesis contents are given as follows.

Chapter 2 is the literature review which includes brief introduction of some types of recoil mechanism, and comparisons for different structures. Besides, there is a simple description about the procedure during firing.

Chapter 3 introduces the force analysis of the gun during firing, especially mathematical descriptions on the recoil force.

Chapter 4 proposes the dynamic analysis and the dynamic model creation of the recoil mechanism. It can be divided into five parts. With free body analyses and experimental data, the dynamic characters can be obtained from system equations. Using Matlab® Simulink, the dynamic model of system equations can be created into individual modulus.

Chapter 5 constructs a simulation model on Simulink®. The simulation results are analyzed with tendency forecasting to match the physical phenomenon. In addition, the simulation chooses some parameters to find the influence of these parameters on the performance of the recoil mechanism. Target and constraints of the optimization problem are defined according to the design requirements. Finally in this chapter, some improvement designs can be obtained by performing optimization.

Chapter 6 provides the concept of controlling the recoil length by controlling orifice area. When the relation between orifice area and recoil length is known, the recoil mechanism can be stopped at the desired recoil length.

Finally, Chapter 7 contains the conclusions and future works, which could assist some aspects for following works on this study.

CHAPTER 2

PRELIMINARY

2.1 Component of the Recoil Mechanism

The system of the recoil mechanism consists of eleven components: recoil piston rod, recoil piston, cushion, dish spring, recoil cylinder, recuperating cylinder, counterrecoil buffer, floating piston, recoil throttling valve, regulator, and regulator valve. All of these components have their respective different functions, which will be introduced in this section. The general functions are introduced as follows [3]:

1. Recoil piston rod: it is a tensile machine part; one end is connected with recoil piston, and the other with breech ring.

2. Recoil piston: the thickness of the piston is controlled by the space of cushion.

3. Cushion: it can prevent the moveable parts such as piston or piston rod from leakage. In Addition, the cushion presses the moveable surface strongly by fluid pressure and spring.

4. Dish spring: it can provide the pressure for the cushion. The dish spring can supply big load with small deformation in a small space.

5. Recoil cylinder: the inner diameter of the cylinder is determined by the diameter of the piston. Moreover, the tube thickness is determined by the pressure which cushion or fluid generates, and by the yielding stress of the material.

6. Recuperating cylinder: this part can store energy, and makes use of gas pressure to return the gun tube to the original position.

7. Counterrecoil buffer: it can be hydraulic or pneumatic. Besides, the buffer controls the velocity of the recuperating stroke.

8. Floating piston: this part is used to separate the liquid and gas in the recuperator cylinder.

9. Recoil throttling valve: this value can be used to control the hydraulic resistance flowing from recoil cylinder to recuperator cylinder.

10. Regulator: a tool, which is installed in the recuperator cylinder, can adjust pressure during recoil and recuperator. Besides, it has to control the flow of hydraulic fluid in any direction.

11. Regulator valve: a tool, which is installed in liquid end of recuperator cylinder, can adjust the flow of hydraulic fluid during recuperating period.

2.2 The Main Types

Because the recoil mechanism was developing for a long time, there are many available devices using in different kinds of guns. There is a general classification, hydrospring and hydropneumatic type, such as shown in Figure 2.2-1. The classification of the recoil mechanism is often seen in the national defense industry.

These two types of the recoil mechanism principally differ from their action components, one is the spring and the other is compressed gas. Generally speaking, recuperator was originally with the spring type [3] [4].

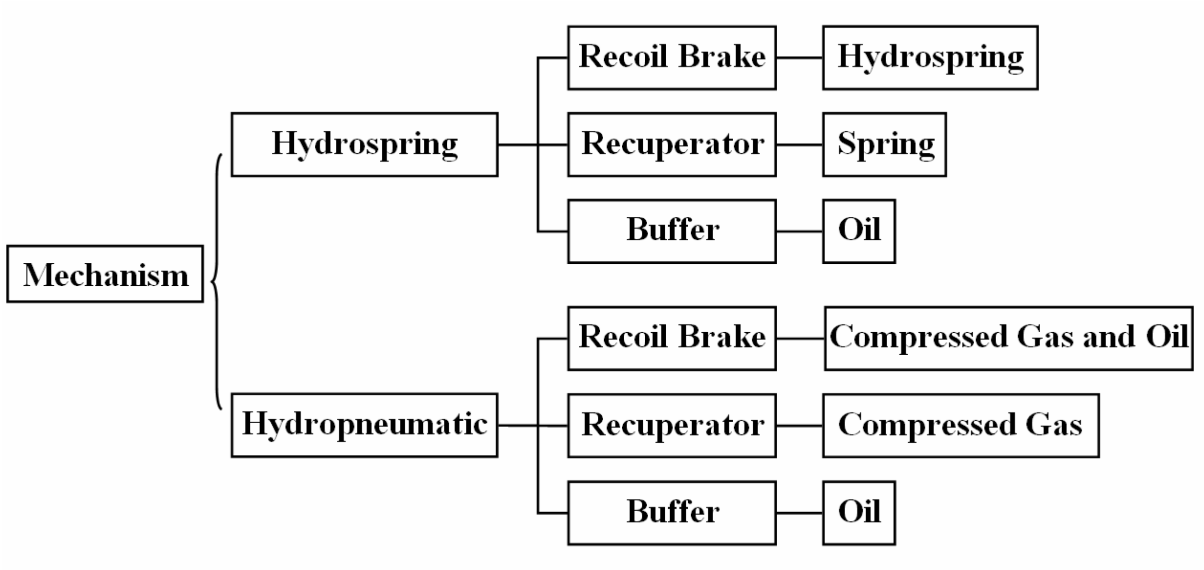


Figure 2.2-1 Classification of recoil mechanism [3]

2.2.1 Hydrospring

The hydrospring system is shown in Figure 2.2-2. There are a recoil brake, a recuperator, and a counterrecoil buffer. In fact, the device consists of two or three parts to ensure the structure more compact. Sometimes, there is a bigger spring which is wound around the barrel to get a more compact assembly.

The recuperator uses a mechanical spring, and the others use hydraulic systems. Although this type is seldom used, there are still some advantages and disadvantage listed in Table 2.2-1. The design of the device is simple, low cost, rapid adjustment, easy manufacture, and there are fewer problems about the airtight leakage. But the life of the spring may not predictable. The volume is huge, and the component replacement is required frequently.

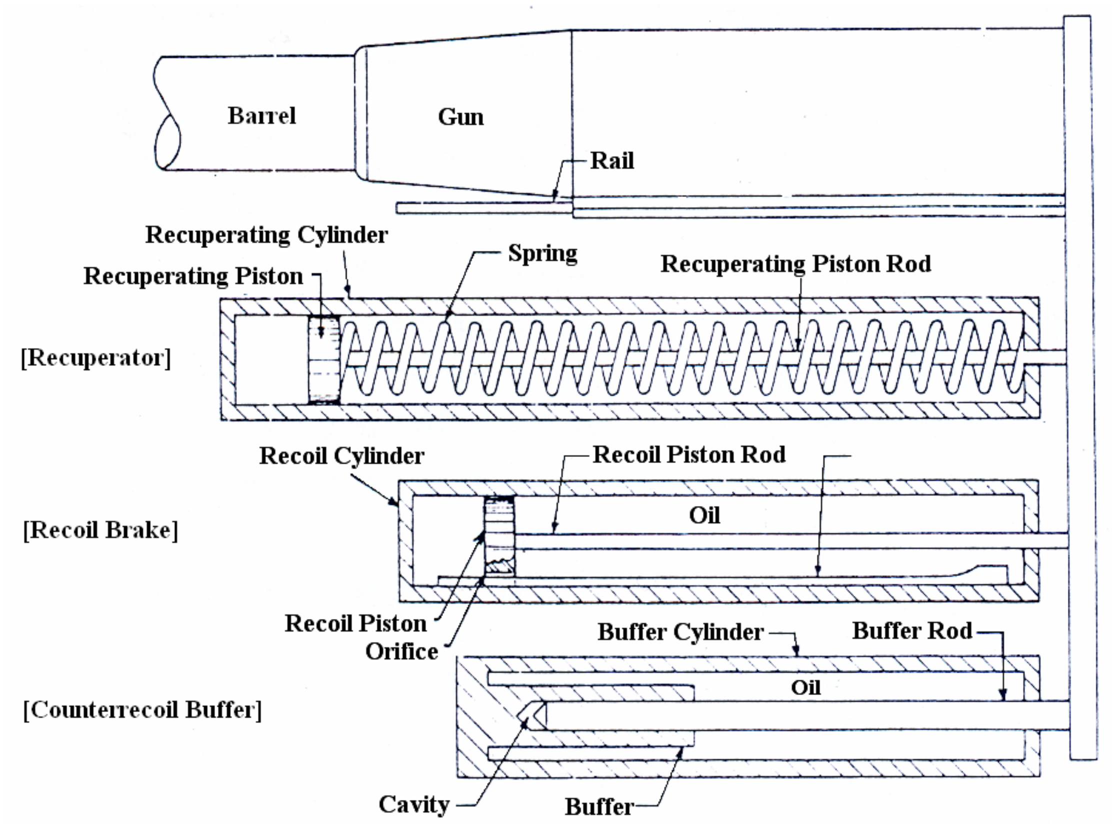


Figure 2.2-2 Hydrospring recoil mechanism [3]

Table 2.2-1 List the features of hydrospring system

Advantages	**Disadvantages**
1. Simple design	1. Maintenance
2. Easy manufacture	2. Big volume
3. Low cost	3. Spring life
4. Rapid adjustment	
5. Fewer airtight leakage	

2.2.2 Hydropneumatic

For the hydropneumatic system, there are two different types: independent and dependent, as shown in Figure 2.2-3 and Figure 2.2-4 respectively. The recuperator fills with compressed gases, and the nitrogen gas is usually used because of its inactivity.

The recuperator of the independent type is separated from recoil brake completely. Furthermore, the piston rods both directly connect with a back part. When the gun recoils, hydraulic fluid or oil will flow to the chamber of compressed gas. The fluid will then press on the gas to make the gas pressure rising, and the action will reverse during the recuperating time.

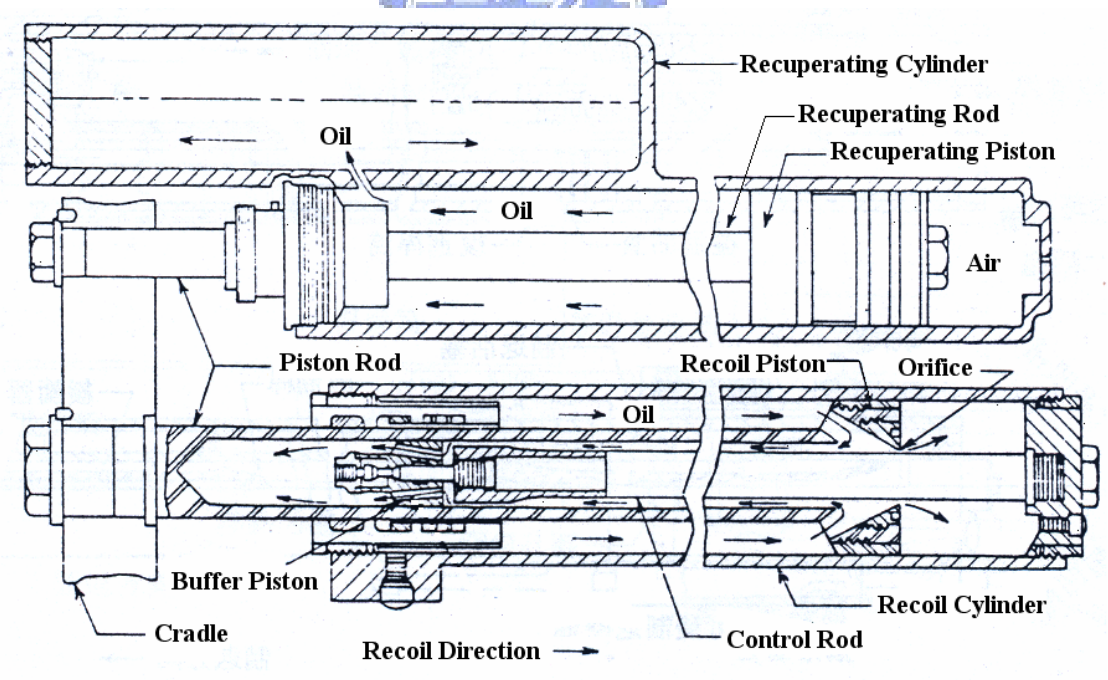


Figure 2.2-3 Hydropneumatic recoil mechanism (independent type) [3]

On the other hand, the recuperator of the dependent type is often connected to the recoil brake, but the gas is separated from fluid by the floating piston. Besides, the recoil piston rod links a back part simply. On the way of throttling, the fluid from recoil cylinder would be pressed on recuperating cylinder. Also, the advantages and disadvantages of the hydropneumatic system are listed in Table 2.2-2. The reliability of the hydropneumatic system is higher, the durability is better, the recoil distance is long, and the design is more flexible. However, the device needs specialized technology and the cost is expansive. In addition, the gas pressure will be easily changed by the atmosphere temperature, and affect the recoil velocity and recoil travel. So it needs some compensation. Moreover, the device is hard to keep the high firing frequency, because of the heat generation.

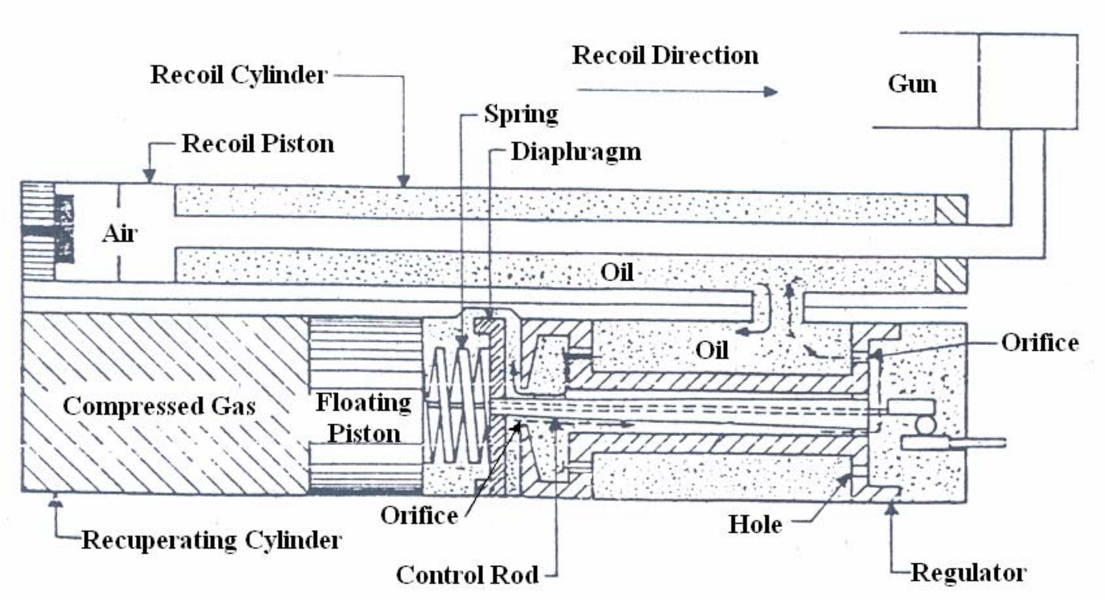


Figure 2.2-4 Hydropneumatic recoil mechanism (dependent type) [3]

Table 2.2-2 List the features of hydropneumatic system

Advantages	Disadvantages
1. High reliability	1. Hard manufacturing
2. Good durability	2. Low firing frequency
3. Flexible application	3. High sensitivity on temperature
4. Long recoil distance	4. High cost
5. Easy maintenance	

2.3 Forces and Procedures during Firing

During firing, a high gas pressure, which acts on the base of the projectile and accelerates it forward, arises in the combustion chamber of the tube. The same gas pressure also acts on the breechblock of the tube, which is forced to the rear with a gas recoil force, which is also called the breech force. The magnitude of this force is the same as the projectile accelerating force. This large gas recoil force on the gun tube does not act directly on the cradle of the tube but on the recoil mechanism.

The gun tube, which is accelerated back by the gas recoil force, is brought to stop by various braking components. These are the hydraulic braking force of the recoil mechanism, the force of the recuperator mechanism, and the friction forces among the components. The braking force acts as a forward direction on the recoil part of the gun to retard the recoil.

The braking of the recoil mechanism generates a mass inertial force, which in magnitude is equal to the total braking force, and acts towards the rear of the gun. Its line of action goes through the center of gravity of the recoiling mechanism of the gun, regardless of where the individual braking force components act on. The recoil braking force knocks the gun backwards, while the baking force is a force which acts on the recoiling part of the gun in forward direction.

After the recoil motion is completed, the recuperating mechanism returns the gun tube to its original position. The required force is provided by mechanical springs or gas cushioning, which are compressed even more beyond their pretensioned state during the recoil of the tube. Therefore, at the end of counterrecoil, the gun gets no moving forward, and the recoil part is braked hydraulically at the end of counterrecoil by means of the recoil brake. The period which recoil force acts is from the projectile firing to the mechanism stopping. Therefore, this period is a complete cycle during firing [5] [6].

CHAPTER 3

FORCE ANALYSIS

3.1 Introduction

All kinds of recoil mechanisms operate according to same basic principles. The apparatus can control forces, through the specific recoil movement. In other words, it makes use of the force to retard the gun tube, and return the gun tube to original position.

When firing, owing to the action of the gas recoil force and the recoil braking force, the load on the gun body often varies from time to time. So, how to solve the force change of the recoil mechanism is a key discussion about this chapter.

Before the force analysis, some assumptions need to be established first. From a physical viewpoint, there is no external force acting on the artillery weapon during firing. The process is the conservation of momentum, and it reflects properties and conditions of the artillery weapon. It also conforms to actual condition of firing. However, the energy conservation principle is difficult to apply because some energy is lost during firing [7].

The resistance force is composed of hydraulic braking force and spring force. Although these two forces act individually, it is treated as a resultant force in the system. Therefore, the overall system can be treated as a unit. Before the problem is defined, some assumptions have to be made as follows:

1. <u>The boundary condition is free release and free recoil.</u>

   The analysis focuses on the motion of the recoil mechanism only. It uses systematic view to analyze the force behavior, and isn't affected by external force of other components.

2. <u>The supporting structure is immovable.</u>

   The supporting structure of the gun body is a rigid body. Its quantity of motion is very small. Thus, the motion of the supporting structure is neglected. It means that the analysis only focus on the first recoil effect.

3. <u>The effect on the muzzle brake is ignored.</u>

   The recoil force is balanced by the muzzle brake and the recoil mechanism. The forces of these two parts are with a proportional relation, such as thirty percent for the muzzle brake and seventy percent for the recoil mechanism. Therefore, the effect on the muzzle brake could be ignored.

4. <u>The analysis focuses on the bore period during firing.</u>

   The bore period means that a projectile moves along the bore of barrel until exiting the muzzle. After a projectile exits the muzzle, the bore pressure would drop to atmospheric pressure gradually. And the influence on recoil force is very small. For this reason, the analysis only focuses on the bore period.

According to the assumptions, the model can be simplified. Then, the equation of motion of the recoil mechanism can be defined. And the analysis of interior ballistics and the recoil motion can combine together so as to find the force conditions of all parts when the projectile exits.

3.2 Equation of Motion

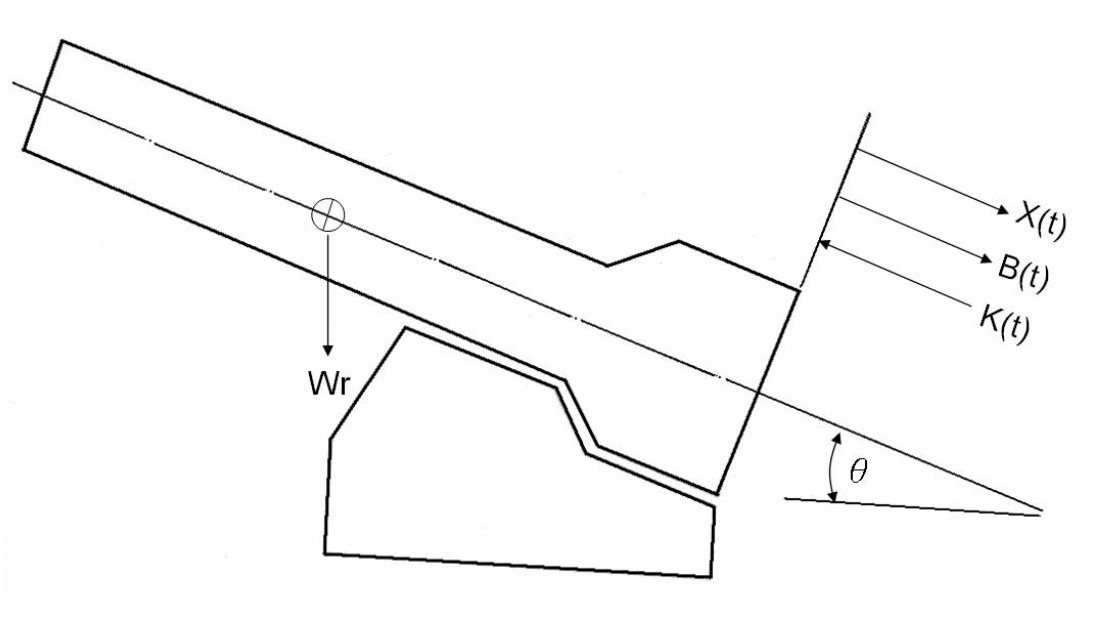


Figure 3.2-1 1-D mode of gun

The equation of motion adopts a mode of single degree of freedom as shown in Figure 3.2-1. According to the Newton's Second Law, the equation of motion of recoil mechanism is

$$\sum F = M_r \ddot{X} = B(t) - K(t) + W_r \sin\theta \quad (3.2\text{-}1)$$

where $\sum F$ is the total force on the recoil mechanism, M_r is the recoil mass, $\ddot{X}$ is the recoil acceleration, $B(t)$ is the breech force, $K(t)$ is the recoil braking force, W_r is the recoil weight force, and θ is the elevation.

$\sum F$ consists of a breech force, a hydraulic braking force, a recuperator force, a frictional force, and the component of the weight, shown in Figure 3.2-2. There are some descriptions about the forces on the recoiling parts during firing:

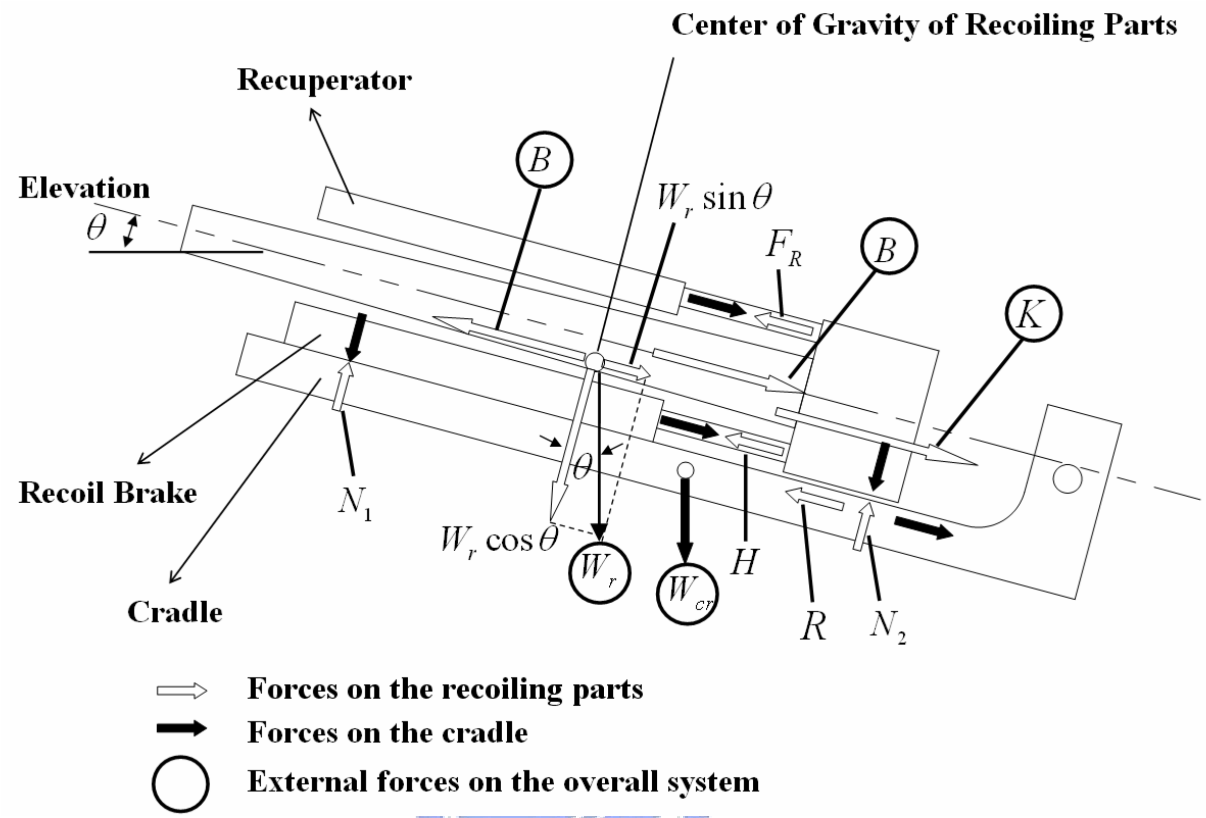


Figure 3.2-2 Forces on the parts moving in elevation

1. Forces acting parallel to the axis of the bore:

(1) Breech force B (on the breechblock)

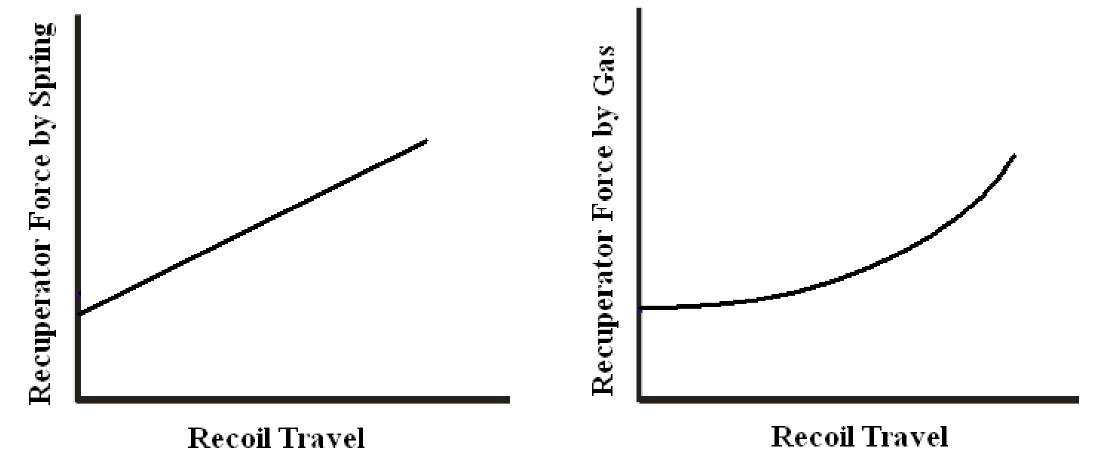
During firing, a high gas pressure arises in the combustion chamber of the tube; it acts on the base of the projectile and accelerates it forward. The same gas pressure also acts on the breechblock of the tube, so it is forced towards the rear as a gas recoil force, also called the breech force. The magnitude is the same as the projectile accelerating force.

(2) Hydraulic braking force H (on the recoil piston rod)

The braking of the recoil piston rod generates a mass inertial force, which acts towards the rear of the gun as a hydraulic braking force. This force can be basically produced by a fluid filled cylinder. Owing to the fact, the cylinder piston coupled to the recoiling masses presses the fluid through a narrow orifice. The magnitude of the force can be controlled by the valve cross-section. In addition, the cross-section and recoil travel have a constant relation.

(3) Recuperator force F_R (on the recuperator piston rod)

The counterrecoil mechanism returns the gun tube to its firing position. The force is often made used of mechanical springs or gas cushioning, which are compressed to store some recoil force during the recoil of the tube. Before firing, the device has to be an initial force in order to resist gravity, and keeps the gun at the original position. Figure 3.2-3 is the relation of the recuperator force and recoil travel. The force seems linear when the spring is used. If a nonlinear force is required, the gas cushion can be used.



(a) By spring (b) By gas cushion

Figure 3.2-3 Curves of recuperator force

(4) Frictional force R (between pistons and the sliding track)

The frictional force is composed of frictions at the piston rod seals on the recoil brake and recuperator, and the piston seal in the recuperator. This force, called the packing friction R_P, is a constant. On the other hand, the sliding track friction of the gun tube R_{SL} is also a component of the frictional force.

(5) Weight component $W_r \sin\theta$ (on the center of gravity of the recoiling parts)

A component of recoil weight is a constant during recoil and recuperating time.

2. Forces acting perpendicular to the axis of the bore:

(1) Guide forces N_1 and N_2 (on the tube claws ,and corresponding sliding surfaces of the gun tube)

The relation between the guide forces and sliding track friction force R_{SL} is

$$R_{SL} = \mu(|N_1| + |N_2|) \tag{3.2-2}$$

where μ is the frictional coefficient, $|N_1|$ and $|N_2|$ are absolutes of the guide forces.

(2) Weight force component $W_r \cos\theta$ (on the center of gravity of the recoiling parts)

A component of recoil weight force is a constant during recoil and recuperating time.

Eq.(3.2-1) shows the combinations of the above-mentioned components. Among these,

$B(t)$ is the breech force B. Besides, $B(t)$ can be indicated by the burning rate of powder as shown in Figure 3.2-4.

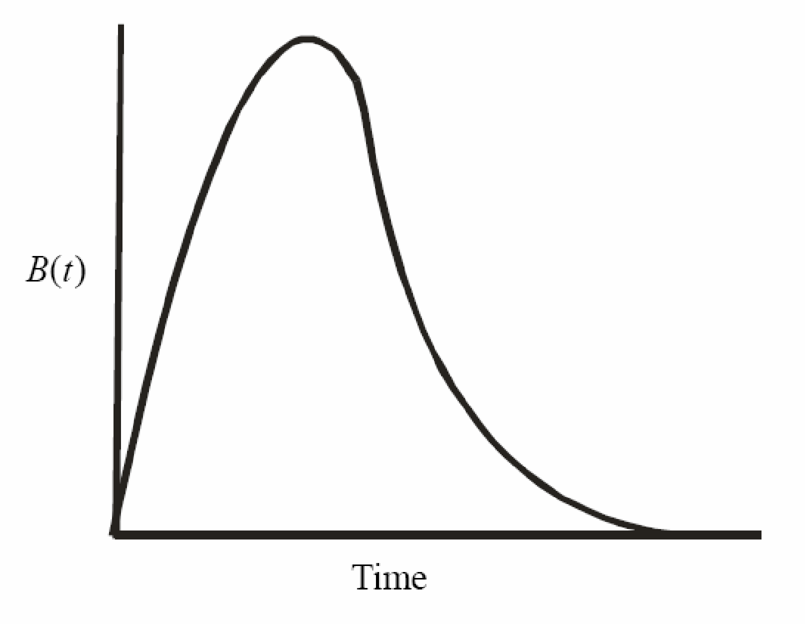


Figure 3.2-4 A Functional relation between $B(t)$ and time

$K(t)$ is the recoil braking force. This means that during the recoil braking, an inertial force $m_R a_R$ has to be applied at the center of gravity of the recoiling parts in the direction of recoil, where a_R is the braking retardation. This backwards directed inertial force is equal to the recoil braking force $K(t)$. From the force equilibrium in the direction of the axis of the bore, the recoil braking force can be expressed as:

$$K(t) = H + F_R + R \quad (3.2\text{-}3)$$

where H is the hydraulic braking force, F_R is the recuperator force, R is the friction force.

3.3 Analysis of Interior Ballistics

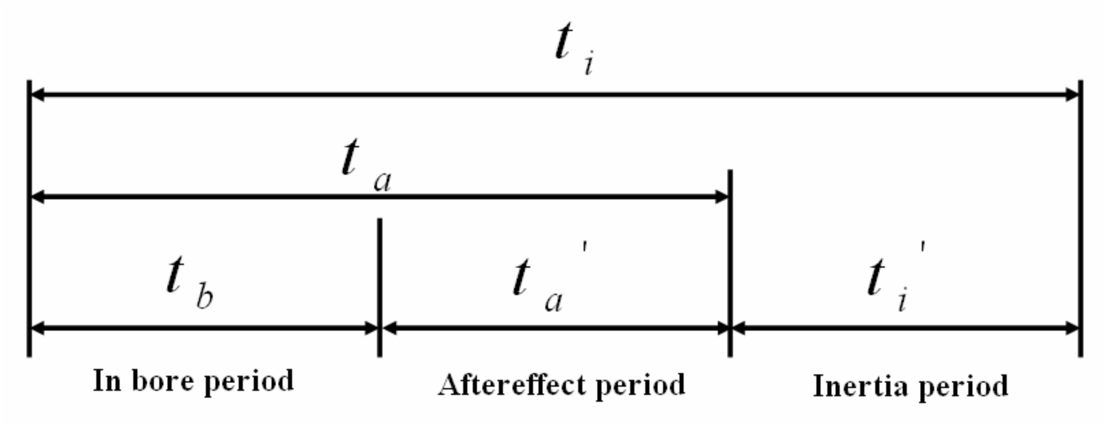


Figure 3.3-1 Three periods of recoil motion

The period of recoil motion, as shown in Figure 3.3-1, can divide into three parts [8] [9]:

1. In bore period

   The period means that a projectile moves along the bore of the barrel until exiting the muzzle. During this period, the motion of the recoil mass is an accelerative motion.

2. Aftereffect period

   This period means that the bore pressure declines to approach the atmosphere pressure, after the projectile leaves the muzzle. During this period, the motion of recoil mass changes from positive to negative acceleration. Besides, the maximum velocity of recoil mass is generated in the period.

3. Inertia period

There is no bore pressure in this period, that is $B = 0$. The recoil mass moves by the inertia force which is remained from the foregoing periods. In addition, the recoil device is retarded by a recoil resistance until the velocity is zero.

There are so many papers to describe the three periods. By the above-mentioned assumption, the analysis here focuses on the in-bore period to get a general theory.

3.3.1 Basic Equations

The basic equations refer to Figure 3.3-2, one listed as follows:

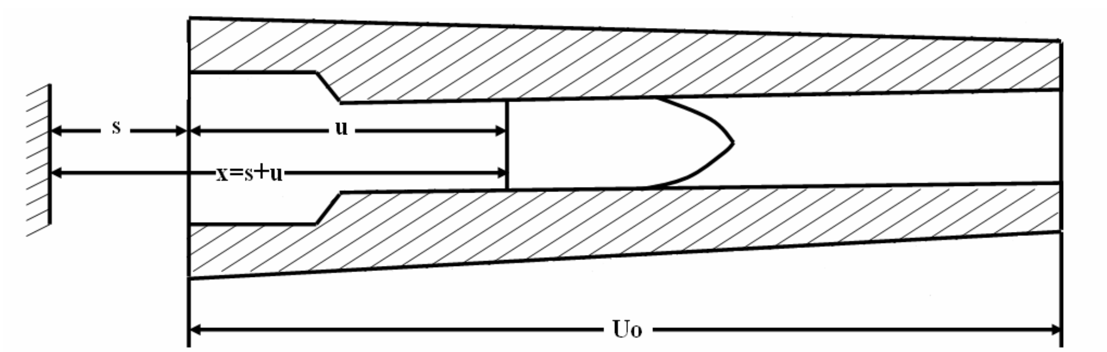


Figure 3.3-2 Moving projectile and barrel

$$x = s + u \tag{3.3-1}$$

$$V = \frac{du}{dt} \tag{3.3-2}$$

$$v = \frac{ds}{dt} \tag{3.3-3}$$

$$P = \frac{B}{A_b} \tag{3.3-4}$$

where x is the absolute displacement of the projectile, s is the absolute displacement of the gun body, u is the projectile travel, V is the projectile velocity, v is the absolute velocity of the gun body, P is the recoil pressure, B is the gas force at the breech (or breech force) A_b is the bore area, and U_0 is the barrel length.

Half mass of the combustion charge acts as the acceleration of a projectile, and the other half as the acceleration of a gun body. There are forces on a projectile and a gun body individually, and the force magnitude is equal but in opposite direction [10].

$$\frac{1}{g}(W_r + \frac{W_c}{2})\frac{dv}{dt} = \frac{1}{g}(W_p + \frac{W_c}{2})\frac{dV}{dt} \qquad (3.3\text{-}5)$$

where W_c is the charge weight force, and W_p is the projectile weight force. Because $\frac{1}{2}W_c$ is much smaller than W_r, so it can be neglected. Eq.(3.3-5) can be written as

$$\frac{dv}{dt} = \frac{(W_p + \frac{W_c}{2})}{W_r}\frac{dV}{dt} \qquad (3.3\text{-}6)$$

In addition, B and F_P can be written as follows:

$$B = \frac{W_r}{g}\frac{dv}{dt} \qquad (3.3\text{-}7)$$

$$F_P = \frac{W_p}{g}\frac{dV}{dt} \qquad (3.3\text{-}8)$$

where B is the gas force at the breech (or breech force), and F_P is the gas force at the base of the projectile.

3.3.2 Determination of Le Duc Parameters: *a* and *b*

The projectile travel and projectile velocity in the bore can be expressed as a hyperbolic function which is also called Le Duc formula, as follows [10]:

$$V = \frac{au}{b+u} \tag{3.3-9}$$

$$\frac{dV}{dt} = \frac{ab}{(b+u)^2}\frac{du}{dt} \tag{3.3-10}$$

By rearrangement of Eq.(3.3-2), Eq.(3.3-7), and Eq.(3.3-10), B can be expressed as Eq.(3.3-11).

$$B = \frac{W_r}{g}\frac{dv}{dt} = \frac{(W_p + 0.5W_c)a^2bu}{g(b+u)^3} \tag{3.3-11}$$

By $\frac{d^2V}{dt^2} = 0$, the maximum breech force is generated when $b = 2u$.

$$B_{\max} = \frac{4a^2(W_p + 0.5W_c)}{27bg} \tag{3.3-12}$$

$$P_{\max} = \frac{B_{\max}}{A_b} = \frac{4a^2(W_p + 0.5W_c)}{27A_b bg} = K\frac{a^2}{b} \tag{3.3-13}$$

where $P_{\max}$ is the maximum bore pressure, and $K = \frac{4(W_p + 0.5W_c)}{27A_b g}$.

According to the muzzle position, U_0 is the barrel length, and V_0 is the muzzle velocity of the projectile. Then the values of a and b are attained as Eq.(3.3-14) and Eq.(3.3-15).

$$b = \frac{aU_0 - V_0U_0}{V_0} \tag{3.3-14}$$

$$a = \frac{U_0P_{\max} \pm \sqrt{(U_0P_{\max})^2 - 4KV_0{}^2U_0P_{\max}}}{2KV_0} \tag{3.3-15}$$

To simplify Eq.(3.3-14) and Eq.(3.3-15), a and b can be expressed as follows:

$$b = QU_0 \tag{3.3-16}$$

$$a = V_0(Q+1) \tag{3.3-17}$$

where $Q = \dfrac{U_0 P_{max} \pm \sqrt{(U_0 P_{max})^2 - 4KV_0^2 U_0 P_{max}}}{2KV_0^2} - 1$.

3.3.3 Projectile Velocity and Breech Force

By rearranging of Eq.(3.3-9), Eq.(3.3-16), and Eq.(3.3-17), the projectile velocity as function of projectile travel is expressed as Eq.(3.3-18).

$$V = \frac{au}{b+u} = \frac{V_0(Q+1)u}{QU_0 + u} \tag{3.3-18}$$

From Eq.(3.3-11), Eq.(3.3-16), and Eq.(3.3-17), the breech force is

$$B = \frac{(W_p + 0.5W_c)V_0^2 (Q+1)^2 QU_0 u}{g(QU_0 + u)^3} \tag{3.3-19}$$

Because the maximum breech force is generated when $b = 2u$, B_{max} is reworded as Eq.(3.3-20).

$$B_{max} = \frac{4(W_p + 0.5W_c)V_0^2 (Q+1)^2}{27QU_0 g} \tag{3.3-20}$$

By rearrangement of Eq.(3.3-19) and Eq.(3.3-20), the simplified breech force is represented as Eq.(3.3-21).

$$B = \frac{27B_{max} Q^2 U_0^2 u}{4(QU_0 + u)^3} \tag{3.3-21}$$

3.3.4 Relationship between Projectile Travel and Time

The time of action is calculated as follows [11]:

From

$$V = \frac{du}{dt} = \frac{au}{b+u}$$

$$dt = \frac{b+u}{au} du$$

By integration of dt,

$$t = \frac{b}{a} \ln u + \frac{u}{a} + c$$

When $u = U_0$, t is zero. So the time is negative before a projectile leaves a muzzle. And

$$c = -\frac{b}{a} \ln U_0 - \frac{U_0}{a}$$

$$t_0 = -\left(\frac{b}{a} \ln \frac{U_0}{u} + \frac{U_0 - u}{a}\right) = -\frac{Q_0 U_0 \ln \frac{U_0}{u} + (U_0 - u)}{V_0 (Q_0 + 1)} \qquad (3.3\text{-}22)$$

But Eq.(3.3-22) makes that the time is negative infinite when the beginning position of projectile ($u = 0$). For this reason, the time which the projectile exits muzzle can be found by the law of impulse and momentum.

$$\overline{B} t_b = \frac{W_r}{g} v_0$$

and

$$v_0 = \frac{W_p + 0.5 W_c}{W_r} V_0$$

where v_0 is the recoil velocity of the gun body when the projectile exits the muzzle, t_b is projectile transit time, and $\overline{B}$ is average breech force. The work of average breech force is

$$\overline{B}U_0 = \int_0^{U_0} F du$$

and using Eq.(3.3-21)

$$\overline{B} = \frac{27}{4} B_{\max} Q^2 U_0 \int_0^{U_0} \frac{u}{(QU_0 + u)^3} du = \frac{27}{8} B_{\max} \frac{Q}{(Q+1)^2} \qquad (3.3\text{-}23)$$

$$t_b = \frac{8(W_p + 0.5W_c)V_0(Q+1)^2}{27 g B_{\max} Q} \qquad (3.3\text{-}24)$$

3.4 Determination of Total Resistance to Recoil

The basic principle of total resistance is assumed that the curve between $K(t)$ and time is a trapezoid as shown in Figure 3.4-1 [6]. Therefore, when the resistance reaches maximum, the value will be supposed as a constant. Therefore, the problem is to find the constant resistance. For this purpose, the section adopts the moment area method [8] [12].

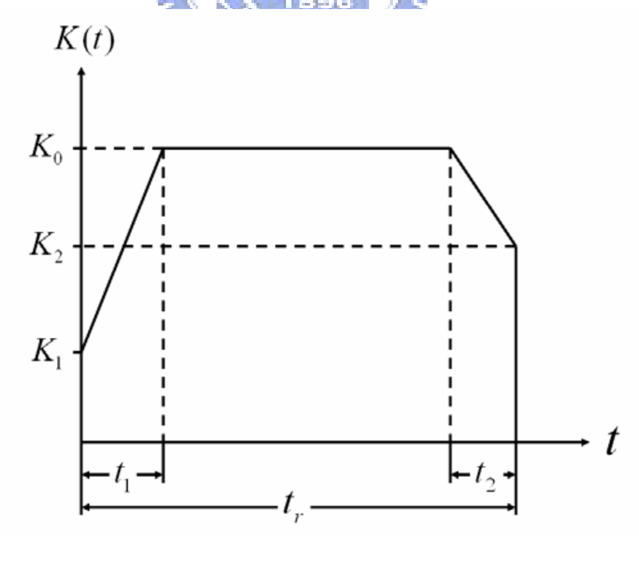


Figure 3.4-1 Practical shape of total resistance to recoil

The moment area method can be used to determine the magnitude of total resistance to recoil, and the recoil time. Then the recoil velocity, which is the function of time or recoil travel, can be calculated easily by the integration of Eq.(3.2-1). Before using the moment area method, the mass of gun body and recoil travel are known, and the relation between breech force and time is also known.

The basic principal of the moment area method is conservation of linear momentum. The recoil mass starts at rest and returns to stop after recoil stroke ends. Hence, the resultant force on the recoil mass has to be zero by linear impulse-momentum law. Consequently, the impulse caused by the breech force and recoil mass must be equal to the impulse of total resistance to recoil in the recoil period. Generally speaking, the law can be expressed as "Impulse in = Impulse out".

The basic motion of equation:

$$\sum F = M_r \ddot{X} = B(t) - K(t) + W_r \sin\theta$$

By integrating one time of above equation,

$$M_r \dot{X} = \int_a^t B(\tau)d\tau - \int_b^t K(\tau)d\tau + (W_r \sin\theta)t \qquad (3.4\text{-}1)$$

Here $B(\tau)$ acts at $t = a$, and $K(\tau)$ acts at $t = b$. For simplifying representations:

$$D(t) = \int_a^t B(\tau)d\tau \qquad (3.4\text{-}2)$$

and

$$H(t) = \int_b^t K(\tau)d\tau \qquad (3.4\text{-}3)$$

where $D(t)$ is the recoil impulse of time t, and $H(t)$ is the total resistant impulse of time t.

By rearrangement of Eq.(3.4-1), Eq.(3.4-2) and Eq.(3.4-3),

$$M_r \dot{X} = D(t) - H(t) + (W_r \sin\theta)t \tag{3.4-4}$$

Integrating Eq.(3.4-4),

$$M_r X = \int_a^t D(\tau)d\tau - \int_b^t H(\tau)d\tau + \frac{1}{2}(W_r \sin\theta)t^2 \tag{3.4-5}$$

Then, integrate the right side of Eq.(3.4-5) as follows:

$$M_r X = \left[\tau D(\tau)\right]_a^t - \int_a^t \tau \frac{dD(\tau)}{d\tau} d\tau - \left[\tau H(\tau)\right]_b^t + \int_b^t \tau \frac{dH(\tau)}{d\tau} d\tau + \frac{1}{2}(W_r \sin\theta)t^2 \tag{3.4-6}$$

or

$$M_r X = tD(t) - \int_a^t \tau B(\tau)d\tau - tH(t) + \int_b^t \tau K(\tau)d\tau + \frac{1}{2}(W_r \sin\theta)t^2 \tag{3.4-7}$$

where $\int_a^t \tau B(\tau)d\tau$ is the moment of areas of breech force, and $\int_b^t \tau K(\tau)d\tau$ is the moment of areas of total resistance to recoil. Therefore, Eq.(3.4-7) can be rewritten as:

$$M_r X = tD(t) - \frac{\int_a^t \tau B(\tau)d\tau}{\int_a^t B(\tau)d\tau} \int_a^t B(\tau)d\tau - tH(t) + \frac{\int_b^t \tau K(\tau)d\tau}{\int_b^t K(\tau)d\tau} \int_b^t \tau K(\tau)d\tau + \frac{1}{2}(W_r \sin\theta)t^2$$

(3.4-8)

In the same way, the above equation can be simplified as follows:

$$\alpha(t) = \frac{\int_a^t \tau B(\tau)d\tau}{\int_a^t B(\tau)d\tau} \tag{3.4-9}$$

$$\beta(t) = \frac{\int_b^t \tau K(\tau)d\tau}{\int_b^t K(\tau)d\tau} \tag{3.4-10}$$

where $\alpha(t)$ which is generated by $B(\tau)$ in time t, is the centroid of the areas, and $\beta(t)$, which is generated by $K(\tau)$ in time t, is the centroid of the areas, shown in Figure 3.4-2.

Then, Eq.(3.4-8) can be rewritten as Eq.(3.4-11),

$$M_r X = tD(t) - \alpha(t)D(t) - tH(t) + \beta(t)H(t) + \frac{1}{2}(W_r \sin\theta)t^2 \tag{3.4-11}$$

or

$$M_r X = [t - \alpha(t)]\int_a^t B(\tau)d\tau - [t - \beta(t)]\int_b^t K(\tau)d\tau + \frac{1}{2}(W_r \sin\theta)t^2 \tag{3.4-12}$$

When recoil stroke finishes, the motion of recoil mass stops. According to the linear impulse-momentum law, some terms can be defined: L is the recoil length, t_r is the time of the recoil stroke, I^* is the total impulse, I_B^* is the impulse of the breech force, $\alpha(t_r)$ is the distance from a beginning to the centroid of area under the curve of breech force, and $\beta(t_r)$ is the distance from a beginning to the centroid of area under the curve of total resistance to recoil.

By using above definitions, Eq.(3.4-1) can be summarized as:

$$I^* = I_B^* + W_r t_r \sin\theta \tag{3.4-13}$$

or

$$\int_{b}^{t_r} K(\tau)d\tau = \int_{a}^{t_r} B(\tau)d\tau + W_r t_r \sin\theta \tag{3.4-14}$$

Eq.(3.4-13) and Eq.(3.4-14) show that the area under the curve of $K(t)$ is equal to the areas under the curves of breech force and recoil weight force as shown in Figure 3.4-2. When the recoil motion finishes, $X = L$, and $t = t_r$. Eq.(3.4-12) can be written as:

$$M_r L = \left[t_r - \alpha(t_r)\right] I_B^{\ *} - \left[t_r - \beta(t_r)\right] I^* + \frac{1}{2}(W_r \sin\theta) t_r^{\ 2} \tag{3.4-15}$$

As a result, Eq.(3.4-14) and Eq.(3.4-15) can be used to decide t_r and $K(t)$.

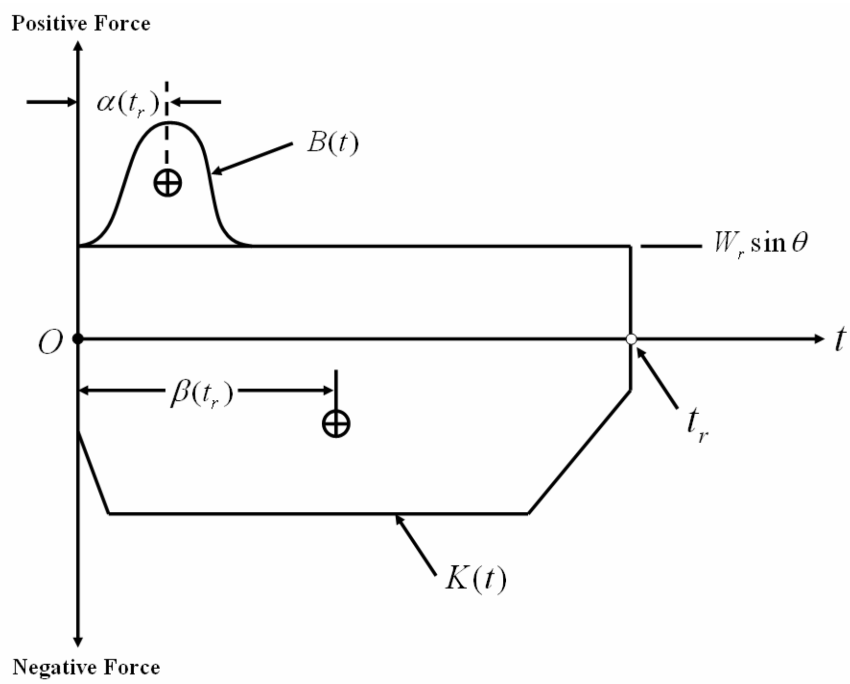


Figure 3.4-2 The curves of $B(t)$, $K(t)$, and $W_r \sin\theta$ [13]

3.5 Forces Contributing to the Total Resistance to Recoil

In the design calculation of the recoil brake, one must start with the total braking force K, where this force is made up of several components, as shown in Section 3.2, Eq.(3.2-3). These components of force include the recuperator force F_R, the sliding track friction R_{SL}, the packing friction R_P, and the hydraulic braking force H. In general, an effort is made to achieve a constant braking force K along the recoil travel. However, a certain rise of the curve must be provided at the beginning and end of the recoil motion.

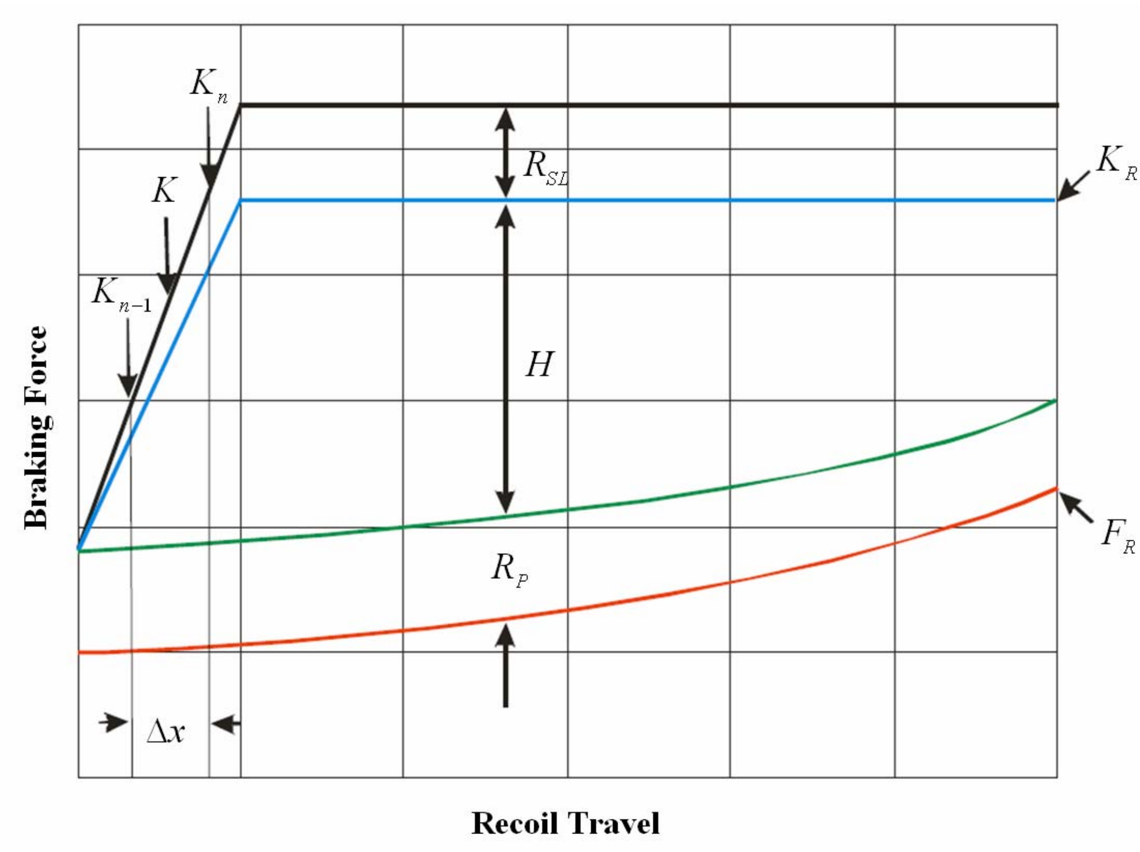


Figure 3.5-1 Curve for the braking force [3] [6]

Figure 3.5-1 is the curve for the braking force. For specified curves for the quantities K, R_{SL}, F_R, R_P, and H, the total braking force:

$$K = K_R + R_{SL} \tag{3.5-1}$$

It can be taken from the diagram as a function of the recoil travel. And $K_R = F_R + R_P + H$ is the rod pull force.

Based on the experience with standard guns, the frictional force is about 3 to 7% of the total braking force K.

3.5.1 The Recuperator Force

The counterrecoil mechanism should return the gun tube, which has recoiled back, to the in-battery position, i.e., the initial position. Pneumatic recuperator is a common recuperator where the gas in the reservoir makes direct contact with fluid used as a transmission and sealing medium, or through a membrane or a floating position not clear.

During the recoil, the gas is polytropically compressed from the initial volume to the final volume. It follows that:

$$P_g V_g^{\ n} = Constant \tag{3.5-2}$$

$$P_i V_i^n = P_x V_x^{\ n} \tag{3.5-3}$$

and

$$n = \frac{C_P}{C_V} \tag{3.5-4}$$

where P_g is the gas pressure, V_g is the gas volume, n is polytropic exponent, P_i is the recuperator gas pressure in battery, P_x is the recuperator gas pressure at x, V_i is the recuperator gas volume in battery, V_x is the recuperator gas volume at x, C_P is the constant pressure specific heat, and C_V constant volume specific heat. In general, the recuperator uses nitrogen, and the polytropic exponent can be taken as $n = 1.6$. Eq.(3.5-3) can be rewritten as:

$$P_x = P_i (V_i / V_x)^n \tag{3.5-5}$$

and

$$V_x = V_i - \Delta V_x \tag{3.5-6}$$

where ΔV_x is increase in V_x, and it is decided by the type of the recoil mechanism. For example, the independent type shown in Figure 2.2-3:

$$\Delta V_x = A_{cr} X \tag{3.5-7}$$

where A_{cr} is the effective area of the recuperating piston, and X is the recoil length.

The dependent type shown in Figure 2.2-4:

$$\Delta V_x = V_i - V_x = A_R X_R = AX \tag{3.5-8}$$

where A_R is the effective area of the recuperating cylinder, X_R is the displacement of control rod, and A is the effective area of the recoil piston.

When P_i and V_i are known, and V_x can be computed by Eq.(3.5-6), Eq.(3.5-7), and Eq.(3.5-8), then P_x will be calculated by Eq.(3.5-5). So, the recuperator force is:

$$F_R = A_R P_x \tag{3.5-9}$$

3.5.2 Frictional Force of Sliding Surfaces

The sliding track friction is generated by the surface friction of rigid bodies at motion. Besides, the magnitude of the force is decided by the frictional coefficient, the recoil length, and the elevation of the gun.

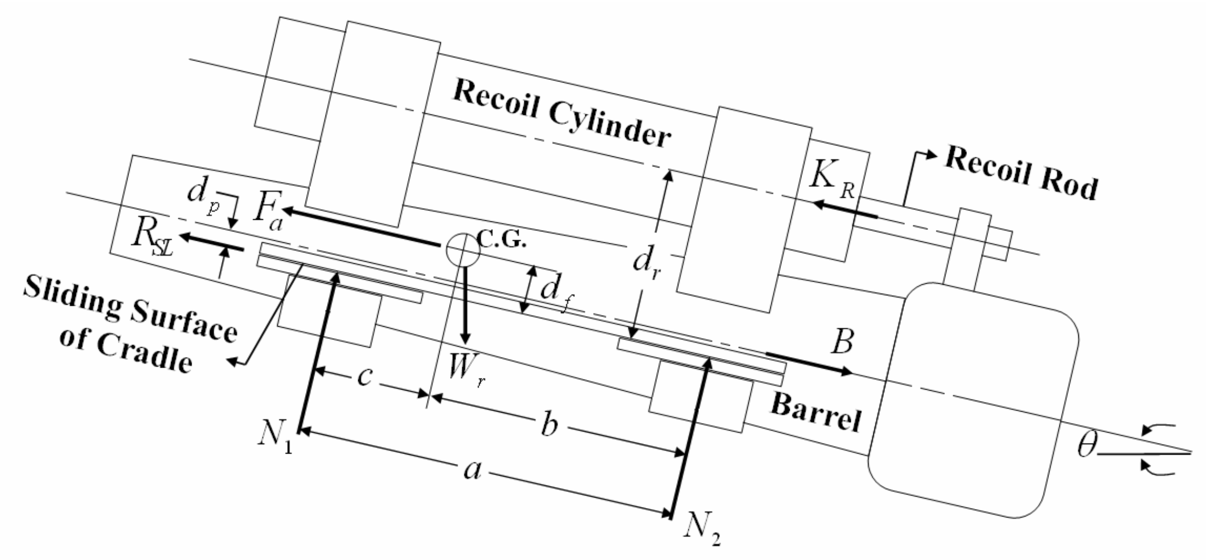


Figure 3.5-2 Sliding track friction on mechanism

Figure 3.5-2 shows the relation between forces and reacting forces of the gun body. In order to calculate the sliding track friction R_{SL}, the guide forces N_1 and N_2 are solved first. Refer to Eq.(3.2-2) $R_{SL} = \mu(|N_1| + |N_2|)$, the frictional coefficient μ can be decided by the relative sliding materials. An intersection point of N_2 and R_{SL} is a pivot, and it can be used to balance the moment.

$$N_1 a + Bd_p + (W_r \sin\theta)d_f = K_R d_r + (W_r \cos\theta)b + F_a d_f \tag{3.5-10}$$

or

$$N_1 = \frac{d_r}{a}K_R + \frac{b}{a}W_r \cos\theta + \frac{d_f}{a}(F_a - W_r \sin\theta) - \frac{d_p}{a}B \tag{3.5-11}$$

where N_1, N_2 are the guide forces, B is the breech force, K_R is the rod pull force, F_a is the inertia force of the recoiling parts, a, b, c are the distances from the center of gravity to the guide forces, and d_p, d_f, d_r are the lengths of the force arm. Furthermore, B and F_a can be gotten from:

$$F_a = B + W_r \sin\theta - K \tag{3.5-12}$$

In addition, the sum force on the vertical direction of the motion is zero. In other words, using the force balance that it means $N_1 + N_2 = W_r \cos\theta$. When $N_1 < W_r \cos\theta$,

$$N_2 = W_r \cos\theta - N_1 \tag{3.5-13}$$

By rearrangement of Eq.(3.2-2), Eq.(3.5-1), Eq.(3.5-12), and Eq.(3.5-13),

$$N_1 = \frac{d_r - d_f}{a} K + \frac{b - \mu d_r}{a} W_r \cos\theta + \frac{d_f - d_p}{a} B \tag{3.5-14}$$

$$N_2 = (1 - \frac{b - \mu d_r}{a}) W_r \cos\theta - \frac{d_r - d_f}{a} K - \frac{d_f - d_p}{a} B \tag{3.5-15}$$

On the other hand, when $N_1 > W_r \cos\theta$,

$$N_2 = N_1 - W_r \cos\theta \tag{3.5-16}$$

By rearrangement of Eq.(3.2-2), Eq.(3.5-1), Eq.(3.5-12), and Eq.(3.5-16),

$$N_1 = \frac{d_r - d_f}{a + 2\mu d_r} K + \frac{b - \mu d_r}{a + 2\mu d_r} W_r \cos\theta + \frac{d_f - d_p}{a + 2\mu d_r} B \tag{3.5-17}$$

$$N_2 = \frac{d_r - d_f}{a + 2\mu d_r} K + (\frac{b - \mu d_r}{a + 2\mu d_r} - 1) W_r \cos\theta + \frac{d_f - d_p}{a + 2\mu d_r} B \tag{3.5-18}$$

3.5.3 Frictional Resistance of Packings

The packing friction is at the piston rod packings on the recoil brake and recuperator, as well as the piston packings in the recuperator. The packings are used to prevent the leakage of the sliding parts. Besides, the packings resist the sliding parts tightly because of the fluid pressure and the action of spring. As a result of the hydrostatic property of packings, the axial pressure of packing is equal to the radial pressure of packing used to prevent the leakage. Moreover, the radial pressure has to be greater than the maximum pressure of the fluid in order to ensure sealing up.

In order to find the packing friction R_P, the radial force of packing on cylinder F_o is needed to know:

$$F_o = A_1 P_R \tag{3.5-19}$$

where $A_1 = \pi D_1 b_1$ is the contact area of packing on cylinder wall, P_R is the radial pressure in packing. In addition, P_R can be rewritten by P_a as follows:

$$P_R = K_p P_a \tag{3.5-20}$$

$$P_a = P_s + P_o \tag{3.5-21}$$

where K_p is the pressure factor depending on material, P_s is the axial pressure produced by spring, and P_o is the fluid pressure on packing at any recoil position. And P_o can be known by conditions of recoil motion. According to the maximum pressure of the fluid, P_s can be expressed as:

$$P_R = \nu P_m = K_p (P_s + P_m) \tag{3.5-22}$$

then

$$P_s = (\frac{\nu}{K_p} - 1)P_m \tag{3.5-23}$$

Where ν is the leakage factor, and P_m is the maximum fluid pressure. By rearrangement of the above-mentioned, the packing friction can be calculated,

$$R_P = \mu F_o \tag{3.5-24}$$

However, the independent type,

$$R_P = R_c + R_r \tag{3.5-25}$$

and the dependent type,

$$R_P = R_c + \frac{A}{A_R} R_r \tag{3.5-26}$$

where R_c is the packing friction of the recoil brake, R_r is the packing friction of the recuperator, A_R is the effective area of the recuperating cylinder, and A is the effective area of the recoil piston.

3.5.4 Hydraulic Baking Force

A hydraulic braking force can be basically developed in a fluid filled cylinder. Owing to the fact, a piston coupled to the recoiling masses presses the displaced fluid through a narrow orifice at recoil motion. From the above-mentioned, the total braking force, the recuperator force, the sliding track friction, and the packing friction are known. According to $K = K_R + R_{SL}$, and $K_R = F_R + R_P + H$, the hydraulic braking force is:

$$H = K - (F_R + R_P + R_{SL}) \tag{3.5-27}$$

3.5.5 Effective Area of the Equivalent Orifice

In a recoil stroke, the fluid has to flow through the connecting ports, piston ports, the orifice, the slots in sleeves, and leakage areas. And all areas the fluid flowing can be equal to the effective areas of a single orifice. In order to understand the relation between the effective areas of an equivalent orifice and the hydraulic braking force, some assumptions on the fluid are established first:

1. Uncompressed fluid.
2. Inviscosity fluid.
3. Steady flow.
4. One-dimensional flow.

For example, the flow velocity of the dependent type through the recoil orifice is,

$$Q_r = Av(x) = C_o a_o v_o(x) \tag{3.5-28}$$

and

$$v_o(x) = \sqrt{2gh(x)} \tag{3.5-29}$$

where Q_r is the rate of flow, A is the effective area of recoil piston, $v(x)$ is the recoil velocity, C_o is the orifice coefficient, a_o is the area of recoil orifice, $v_o(x)$ is the velocity of flow through orifice, g is the acceleration of gravity, and $h(x)$ is the velocity head at x position.

Now, the increase in $P(x)$ generated by the orifice is,

$$\Delta P(x) = P_b - P_{rx} \tag{3.5-30}$$

and

$$\Delta P(x) = \omega h(x) \tag{3.5-31}$$

where P_b is the fluid pressure of recoil cylinder, P_{rx} is the gas pressure at any position of recoil, and ω is the density of fluid. By rearrangement of Eq.(3.5-29), Eq.(3.5-31), $v_o(x)$ can be rewritten as:

$$v_o(x) = \sqrt{\frac{2g\Delta P(x)}{\omega}} \tag{3.5-32}$$

Also, the area of recoil orifice can be rewritten by Eq.(3.5-28), and Eq.(3.5-32):

$$a_o = \frac{Av(x)}{C_o v_o(x)} = \frac{Av(x)}{C_o}\sqrt{\frac{\omega}{2g\Delta P(x)}} \tag{3.5-33}$$

As a result of $\Delta P(x)$ can be gotten by:

$$\Delta P(x) = H(x)/A \tag{3.5-34}$$

where $H(x)$ is the hydraulic braking force generated by the orifice. Now, the effective area of an equivalent orifice can be defined as:

$$a_e = C_o a_o \tag{3.5-35}$$

Then, by rearrangement of Eq.(3.5-33), and Eq.(3.5-35):

$$a_e = Av(x)\sqrt{\frac{\omega}{2g\Delta P(x)}} = Av(x)\sqrt{\frac{\omega A}{2gH(x)}} \tag{3.5-36}$$

Eq.(3.5-36) means that all fluid flows through the orifice. But if some fluid remains on the gap of the control rod, Eq.(3.5-36) will be rewritten as follows:

$$a_e = A(1-\frac{A_C}{A_R})v(x)\sqrt{\frac{\omega}{2g\Delta P(x)}} = A(1-\frac{A_C}{A_R})v(x)\sqrt{\frac{\omega A}{2gH(x)}} \tag{3.5-37}$$

where A_C is the cross-section area of the control rod, and A_R is the effective area of the recuperating cylinder.

3.6 Remarks

1. In this chapter, all forces on the recoil mechanism are mentioned, and their relations are stated clearly.

2. The basic principles and mathematical calculations of each force are introduced. From this, many parameters which will influence the recoil mechanism are known, as shown in Table 3.6-1.

3. In accordance with the theory of each important part, the mathematical model of the recoil mechanism has its completeness and reliability.

4. Before analyzing or designing, it can check the mathematical theory of the model. The checking process ensures that the product can be not only supported by original information, but also designed correctly.

Table 3.6-1 List all force and parameters of the recoil mechanism

Force Name	Parameters
Breech force	W_P, W_C, $P_{\max}$, V_0, U_0, A_b
Total braking force	$K = H + F_R + R_P + R_{SL}$
● Hydraulic braking force	A, $\dot{X}$, a_e, g, ω
● Recuperator force	A_R, P_i, V_i, X, n
● Packing friction	A_1, K_p, P_m, μ, υ
● Sliding track friction	W_r, X, θ, μ
Weight force	W_r, θ

CHAPTER 4

SYSTEM DYNAMIC MODELING

4.1 Introduction

In this chapter, dynamic characters of the recoil mechanism are analyzed, and dynamic models from system equations are implemented in Matlab® Simulink.

Two main methods are used for the dynamic model creation. First, the free body analysis is applied on the system components because the required forces can be found easily. Forces can be treated as internal or external ones according to the free body setup. If the component is too complex to find its physical or mathematical model, it can be treated as a "black box" in the second stage. In such black boxes, experience data and curve fitting methods are used to create the relation that supports for dynamic system. Only input data and output responses are used for analysis, such as the equivalent orifice, the situation of sliding surface, the affect of all packing, and etc. The dynamic models are similarly built in Simulink® according to the equations developed in section 4.2 and 4.3.

In order to simplify the models, some assumptions are supposed in the free body analyses. First, all the components are treated as rigid bodies. Second, the friction forces between the components are ignored. Let these friction forces be constant.

4.2 Dynamic Analysis of the Recoil Mechanism

The complete theory of recoil mechanism is stated in chapter 3. The dynamic model is setup according to the M178 recoil mechanism on the M109 155mm self-propelled howitzer. This artillery is on active duty including in many countries. Its recoil mechanism is the hydropneumatic type, as shown in Figure 2.2-3 or Figure 2.2-4. Furthermore, the counterrecoil mechanism is the independent type, as shown in Figure 2.2-3. This counterrecoil mechanism, in which the recoil and counterrecoil systems are not connected by an oil passage, is commonly used on all medium and heavy field artillery weapons.

4.2.1 Structure of Dynamic System

The structure of the recoil mechanism is shown in Figure 4.2-1. The original mechanism contains too many components. In order to simplify the model, it can be divided into three parts. And clear dynamic diagrams can refer to Figure 3.2-2 and Figure 3.5-2. All forces are generated by three main parts: recoiling part, recoil brake, and recuperator. In fact, recoiling part include all recoil components, such as recoil brake, counterrecoil mechanism, etc.. But here, three parts can be seen as the main mechanism that generates individual force: the breech force, the hydraulic braking force, and the recuperator force. Before discussing the main forces, sliding track friction and packing friction can be talked first.

The sliding track friction is generated by the surface friction of components at motion. Besides, the magnitude of this force is decided by the frictional coefficient, the recoil length, and the elevation of the gun. Fluid packings in the recoil brake prevent leakage of the moving parts, such as pistons and piston rods. The fluid packings are forced firmly against the moving surfaces both by the pressure of the fluid itself and by spring. Therefore, the packing friction is generated during component movement. The two forces account for three to five percent of total braking force. So they will be treated as constant forces here [3].

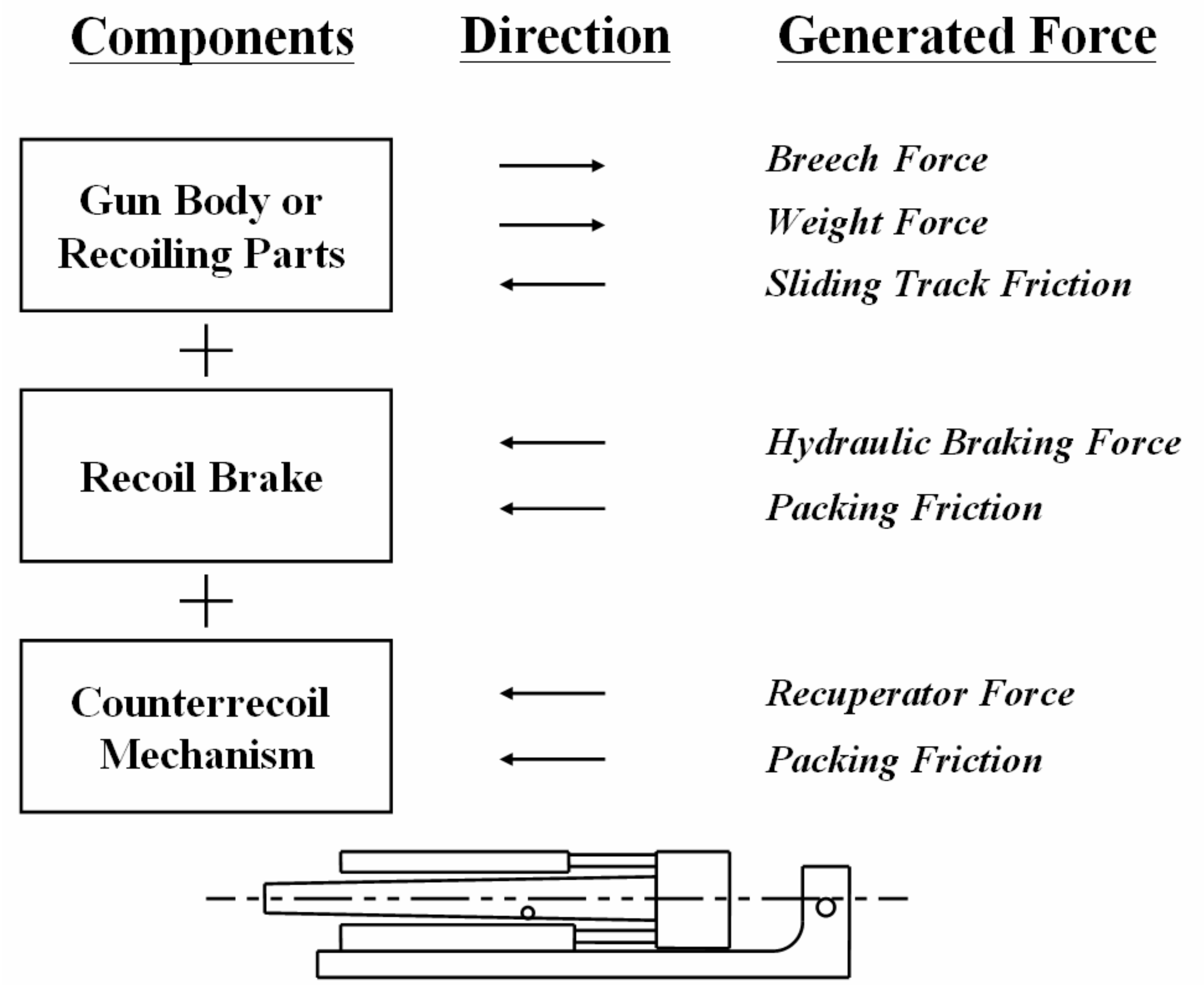


Figure 4.2-1 Simple structure of recoil mechanism

4.2.2 Recoiling Parts

Recoiling parts are the general name of all recoiling components. It is affected by the propellant gas forces. As the gas pressure propels the projectile toward the muzzle, it exerts an equal value and opposite direction force on the breech, which tends to drive the gun backward. Besides, this motion is resisted by the friction of the recoiling part. And, the weight of the recoiling part also accelerates this motion. Thus, the dynamic equations of the system are listed below.

● **Breech force** – It is a reacting force of the propellant gas forces. The dynamic equations are rearranged and reference to section 3.3.

$$B=\frac{27B_{\max}Q^2U_0{}^2u}{4(QU_0+u)^3}=\frac{(W_p+0.5W_c)a^2bu}{g(b+u)^3} \qquad (4.2\text{-}1)$$

where

$$B_{\max}=\frac{4(W_p+0.5W_c)V_0{}^2(Q+1)^2}{27QU_0g}\,,\quad Q=\frac{U_0P_{\max}\pm\sqrt{(U_0P_{\max})^2-4KV_0{}^2U_0P_{\max}}}{2KV_0{}^2}-1\,,$$

$$a=V_0(Q+1)\,,\quad b=QU_0\,,\quad K=\frac{4(W_p+0.5W_c)}{27A_bg}\,,\quad P_{\max}=\frac{B_{\max}}{A_b}=K\frac{a^2}{b}\,.$$

And

$$t=t_b+t_0=\frac{8(W_p+0.5W_c)V_0(Q+1)^2}{27gB_{\max}Q}+\left(\frac{b}{a}\ln\frac{U_0}{u}+\frac{U_0-u}{a}\right) \qquad (4.2\text{-}2)$$

Now, Eq.(4.2-1) represents that breech force is the function of projectile travel. And Eq.(4.2-2) also represents that time is a function of projectile travel. With rearranging the Eq.(4.2-2), projectile travel can be expressed as a function of time, shown in Eq.(4.2-3). It will help that breech force can be the function of time later.

$$b*lambertw\left(\frac{U_0*\exp\left(\frac{t*a-tb*a+U_0}{b}\right)}{b}\right) \qquad (4.2\text{-}3)$$

where the *lambertw* is the function of Matlab®.

- **<u>Weight force</u>** – A component of recoil weight is a constant during recoil and recuperating time. And weight component is

$$W_r\sin\theta \qquad (4.2\text{-}4)$$

4.2.3 Recoil Brake

The recoil brake controls the recoil motion of the weapon. It consists of a piston which moves in a cylinder filled of oil. When the tube recoils, there is a relative motion between the piston and the cylinder. As the piston moves within the cylinder, a force is generated by restricting the flow of hydraulic fluid from pressure chamber of the cylinder. The magnitude of this restricting force is a function of the fluid flow through one or more orifices, whose size is regulated to provide the desired recoil velocity and pressure curve. The recoil energy absorbed by this restricting force is dissipated as heat.

- **Hydraulic braking force** – The braking of the recoil piston rod generates a mass inertial force, which acts towards the rear of the gun as a hydraulic braking force. The dynamic equations are rearranged and reference to section 3.5.4 and section 3.5.5.

$$H = \frac{A^3 v^2 \omega}{2{a_e}^2 g} = \frac{A^3 \dot{X}^2 \omega}{2{a_e}^2 g} \tag{4.2-5}$$

where A is the effective area of the recoil piston, $\dot{X}$ is the recoil velocity, ω is the density of fluid, a_e is the effective area of orifice area, g is the acceleration of gravity.

4.2.4 Counterrecoil Mechanism

The counterrecoil mechanism is composed of a recuperator and a counterrecoil cylinder assembly. The terms counterrecoil mechanism and recuperator are sometimes used as synonyms. However, to avoid confusion, the recuperator is defined here as the equipment which stores some of the recoil energy for the counterrecoil motion. The counterrecoil cylinder is defined as the unit which returns the recoiling parts to battery. It provides its energy from the recuperator. There is always some recuperator force to hold the recoiling parts in battery at all angles of elevation.

- **Recuperator force** – The gas is compressed further, storing the additional energy needed for counterrecoil. The dynamic equations are rearranged and reference to section 3.5.1.

$$F_R = A_R P_i \left(\frac{V_i}{V_i - A_R X}\right)^n, \qquad (4.2\text{-}6)$$

where A_R is the effective area of the recuperating cylinder, P_i is the recuperator gas pressure in battery, V_i is the recuperator gas volume in battery, X is the recoil length, n is the polytropic exponent.

4.3 Dynamic Model Creation

There are many commercial packages available to create dynamic models and do dynamic analysis, for example: Adams®, Working Model®, and so forth. This study here needs to combine both dynamic problems, and optimization problems. The best way to solve all these problems integrally is to solve by mathematical methods. Matlab® is used a mathematically based engineering package produced by Math Work. Besides, one of its modules, Simulink® is able to create the system equations.

4.3.1 Matlab Simulink

Simulink® is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. System equations can be created into block diagrams according to the mechanical structure. Many built block diagrams can be combined into a subsystem to simplify a complete system. Block and block are connected by transfer lines defined in Simulink®. Each transfer line has one end of input and one or more ends of output. Furthermore, the combination of these block diagrams can be in the form of close loop which iterations are done automatically in the system.

4.3.2 Module Creation

In this subsection, dynamic models of recoil mechanism are created into Matlab Simulink, and program models are built by each component mentioned previously. Especially, sliding track friction and packing friction are small compared to the total model. So they are assumed as a constant, and not considered below.

Recoiling Parts

- **Breech force**

The system equation of the breech force is shown in Eq.(4.2-1). It describes the relation between the breech force and the projectile travel. In this equation, all parameters are mathematical operations. According to these relations, the breech force can be obtained from Eq.(4.2-1). The block diagrams in terms of the mathematical relations in Simulink® are shown in Figure 4.3-1.

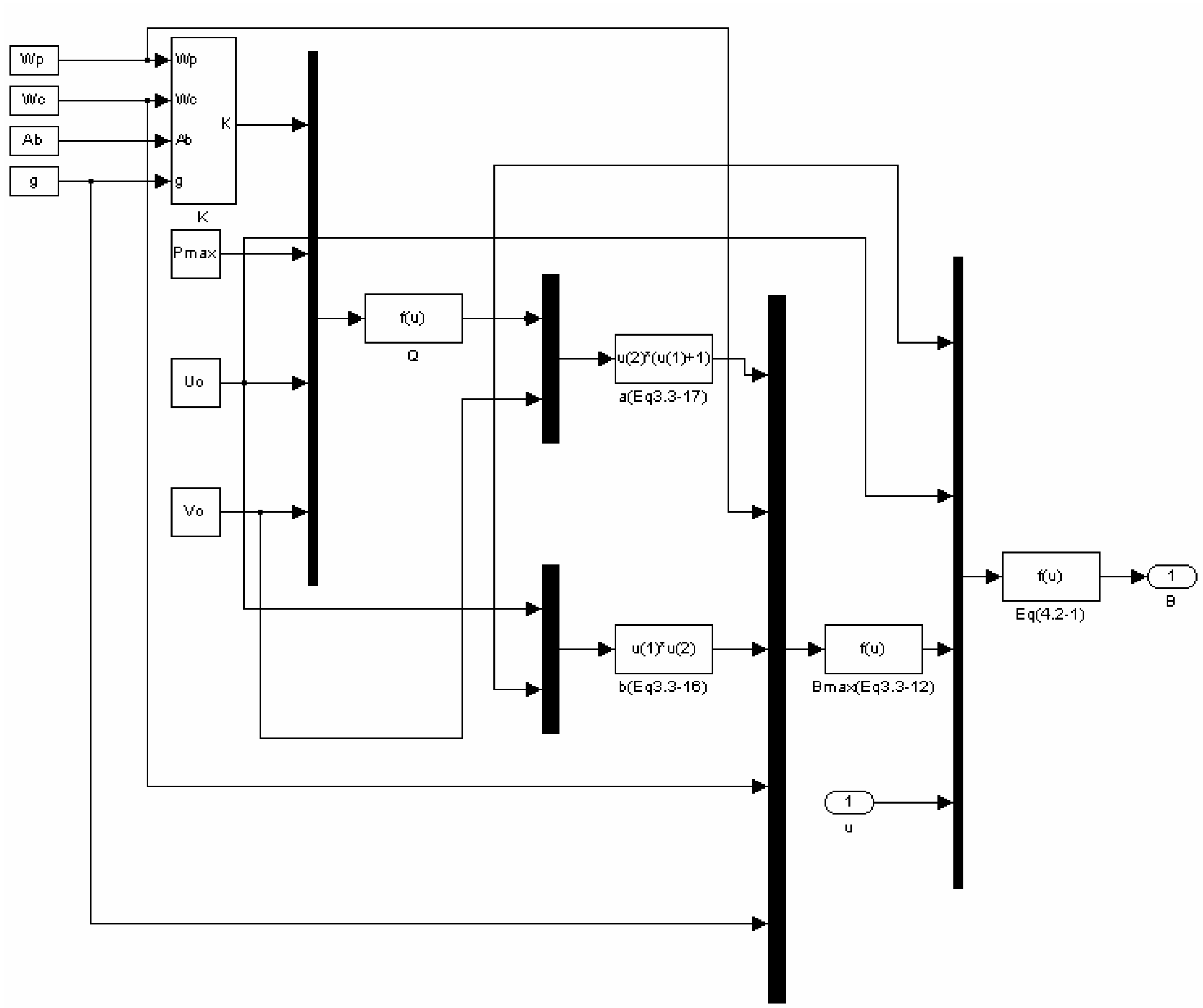


Figure 4.3-1 Breech force in Simulink® model

By combining these block diagrams, system dynamic equations of the breech force can be created into a breech force module, as shown in Figure 4.3-2.

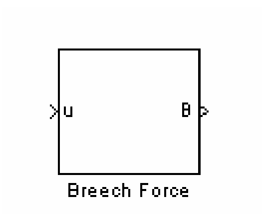


Figure 4.3-2 Breech force module

The system equation of the relation between time and projectile travel is shown in Eq.(4.2-2). In this equation, all parameters are mathematical operations. According to these relations, projectile travel can be transferred as a function of time. The block diagrams in terms of the mathematical relations in Simulink® are shown in Figure 4.3-3.

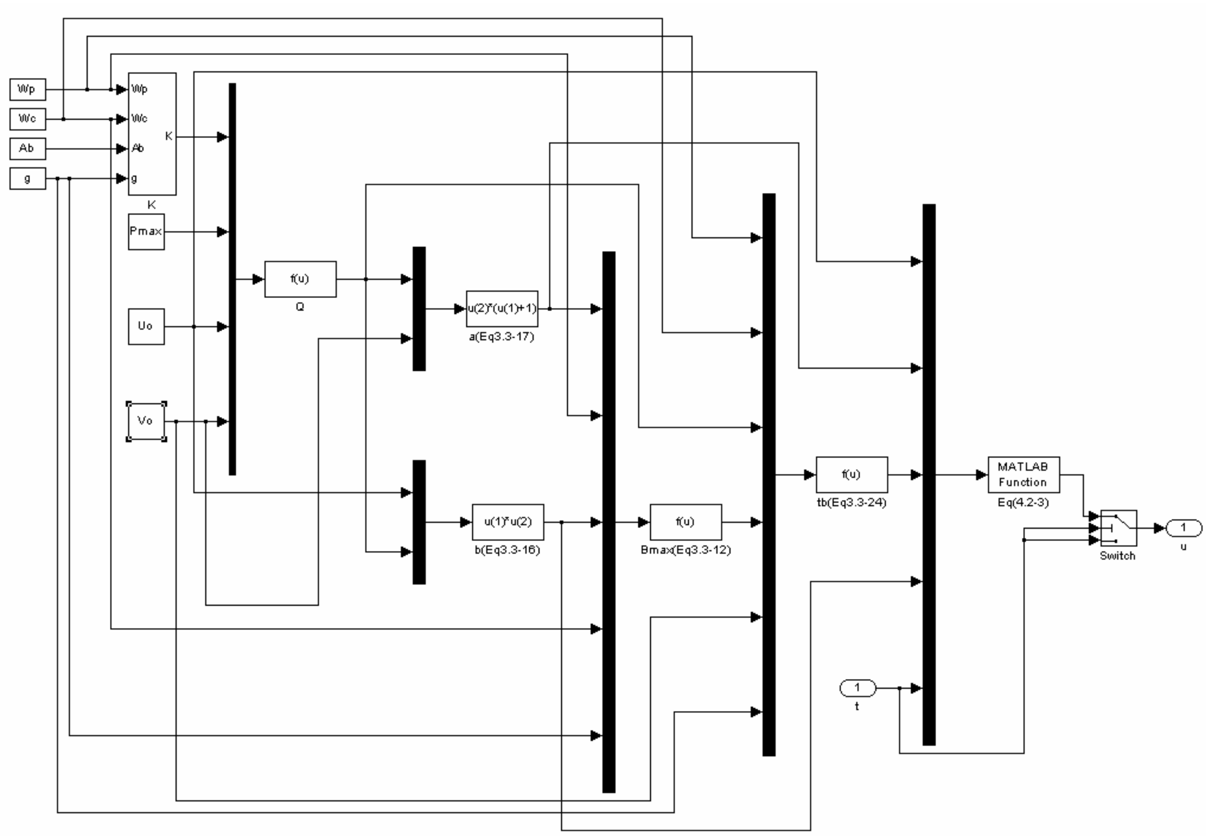


Figure 4.3-3 Relation between time and projectile travel in Simulink® model

By combining these block diagrams, system dynamic equations of time and projectile travel can be created into a t_u transfer module, as shown in Figure 4.3-4.

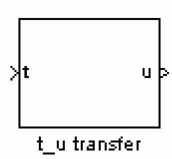


Figure 4.3-4 Time and projectile travel transfer module

Because the breech force is a function of time originally, it can't just represent by the projectile travel. Hence, rearranging the Eq.(4.2-1) and Eq.(4.2-3), projectile travel can be transformed as a function of time, as shown in Eq.(4.2-3). Combining the two modules, the breech force can be expressed as a function of time, as shown in Figure 4.3-5.

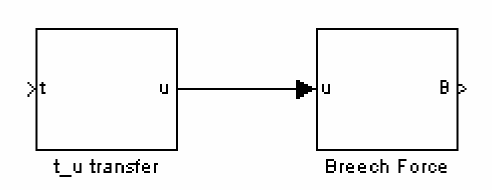


Figure 4.3-5 Time and breech force transfer module

The parameters in this module are stated in Table 4.3-1.

Table 4.3-1 Parameter table of the breech force

Input	t
Output	B
System Parameters	W_p , W_c , A_b , g , $P_{\max}$, U_0 , V_0 , Q , a , b , $B_{\max}$, K , tb

- **<u>Weight force</u>**

The system equation of the weight is constant. Therefore, it can be a function of the elevation angle, as shown in Figure 4.3-6.

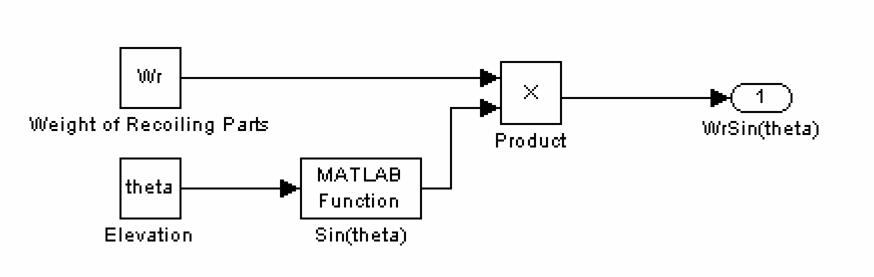


Figure 4.3-6 Weight force in Simulink® model

Recoil Brake

- **Hydraulic braking force**

The system equation of the hydraulic braking force is shown in Eq.(4.2-5). According to the equation, hydraulic braking force can be obtained from Eq.(4.2-5). The block diagrams in terms of the mathematical relations in Simulink® are shown in Figure 4.3-7.

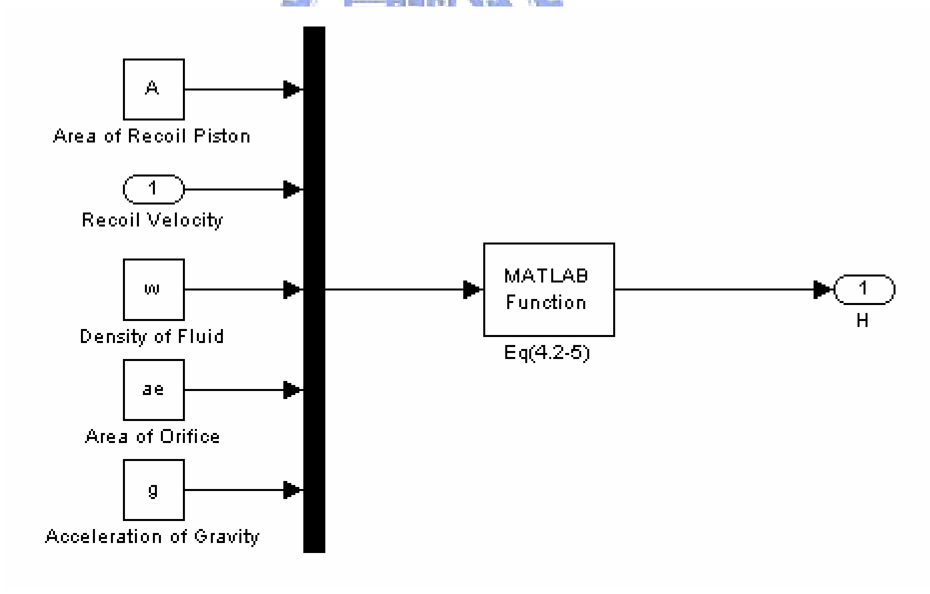


Figure 4.3-7 Hydraulic braking force in Simulink® model

By combining these block diagrams, system dynamic equations of the hydraulic braking force can be created into the hydraulic braking force module, as shown in Figure

4.3-8. The parameters in this module are stated in Table 4.3-2.

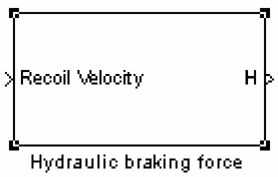


Figure 4.3-8 Hydraulic braking force module

Table 4.3-2 Parameter table of the hydraulic braking force

Input	$\dot{X}$
Output	H
System Parameters	A, ω, ae, g

Counterrecoil Mechanism

- **Recuperator force**

The system equation of the recuperator force is shown in Eq.(4.2-6). In this equation, all parameters are in mathematical expressions. According to these relations, the recuperator force can be obtained from Eq.(4.2-6). The block diagrams in Simulink® are shown in Figure 4.3-9.

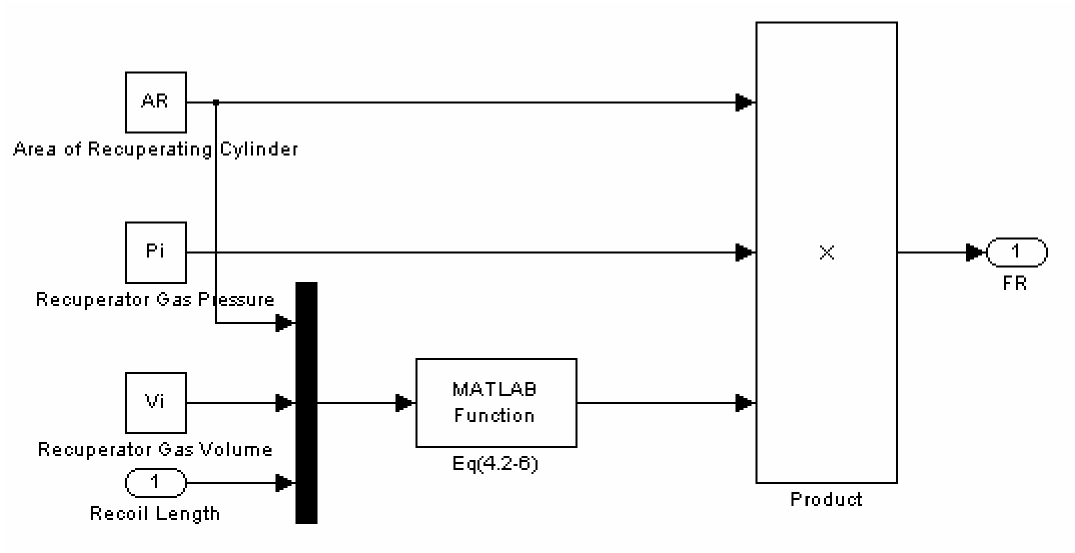


Figure 4.3-9 Recuperator force in Simulink® model

By combining these block diagrams, the system dynamic equations of the recuperator force can be created into the recuperator force module, as shown in Figure 4.3-10. The parameters in this module are stated in Table 4.3-3.

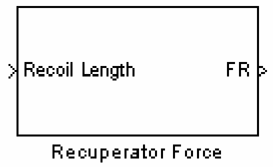


Figure 4.3-10 Recuperator force module

Table 4.3-3 Parameter table of the recuperator force

Input	X
Output	F_R
System Parameters	A_R , Pi , Vi , n

4.3.3 Parameter Settings

In order to simulate the built models, system parameters displayed in Table 4.3-1, Table 4.3-2, and Table 4.3-3 have to be determined in this section. Most dimensions of components have been defined in the original design of M178 recoil mechanism [3]. Such parameters can be set directly. Some structure parameters are too complex, such as the effective area of the orifice which will be determined by measurement data.

Parameters of recoiling parts, recoil brake and recuperator are shown in Table 4.3-4 and Table 4.3-5.

Table 4.3-4 List of parameters assigning in the recoiling parts

Description	**Unit**	**Notation**	**Value**
Bore area	in^2	A_b	29.75
Acceleration of gravity	$in/\sec^2$	g	386
Maximum bore pressure	psi	$P_{\max}$	47000
Sliding track friction	lb	R_{SL}	1018
Barrel length	in	U_0	200
Muzzle velocity of the projectile	$in/\sec$	V_0	32520
Charge weight force	lb	W_c	35.48
Projectile weight force	lb	W_P	96
Weight of recoiling parts	lb	W_r	4360
Mass of recoiling parts	$lb\cdot\sec^2/in$	M_r	11.2942
Elevation	$\circ$	θ	45

Table 4.3-5 List of parameters assigning in the recoil brake and recuperator

Description	**Unit**	**Notation**	**Value**
Effective area of the recoil piston	in^2	A	32.976
Effective area of the recuperating cylinder	in^2	A_R	9.724
Polytropic exponent	None	n	1.6
Recuperator gas pressure in battery	psi	Pi	650
Packing friction	lb	R_P	2340
Recuperator gas volume in battery	in^3	Vi	1015
Density of fluid	lb/in^3	ω	0.0313

On the other hand, the relation between the recoil length and the orifice area is obtained from measurement data [6], as shown in Table 4.3-6. In Simulink®, these data are imported in the lookup table block. The block uses Interpolation-Extrapolation [14]. This is the default method in Matlab®, and it performs linear interpolation and extrapolation of the inputs. And finally, the important input of the complete model is time. It is usually about 0 to $0.2 sec$.

Table 4.3-6 Parameters from measurement data

X	0	1	2	3	5	6	7	8	9	10	11
ae	0.5	2.3	2.9	3.2	3.5	3.4	3.15	3.1	3	2.9	2.8

X	12	13	14	15	16	17	18	19	20	21	22
ae	2.7	2.6	2.56	2.5	2.4	2.3	2.26	2.19	2.1	2.07	2

X	23	24	25	26	27	28	29	30	31	32	33
ae	1.88	1.79	1.76	1.65	1.58	1.5	1.36	1.32	1.15	1.06	0.85

X	34	35	36
ae	0.66	0.5	0.5

4.3.4 Module Combination

Combine both input and output parameters of modules created above, a system model of recoil mechanism can be obtained. The system includes modules of the breech force, the hydraulic braking force, the recuperator force, the weight force, the sliding track friction, and the packing friction. The combined system is shown in Figure 4.3-11. The main logic of module combination is simple and its procedure can be shown in Figure 4.3-12.

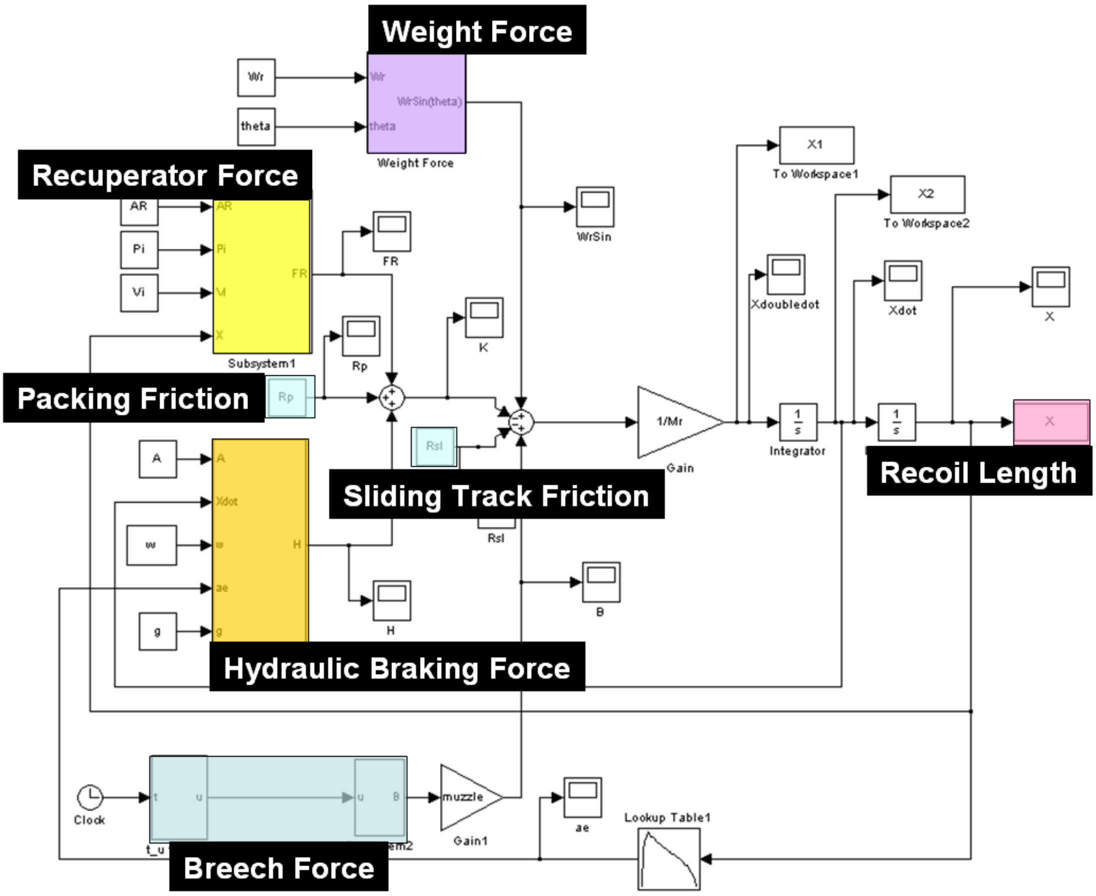


Figure 4.3-11 Combined system model of the recoil mechanism

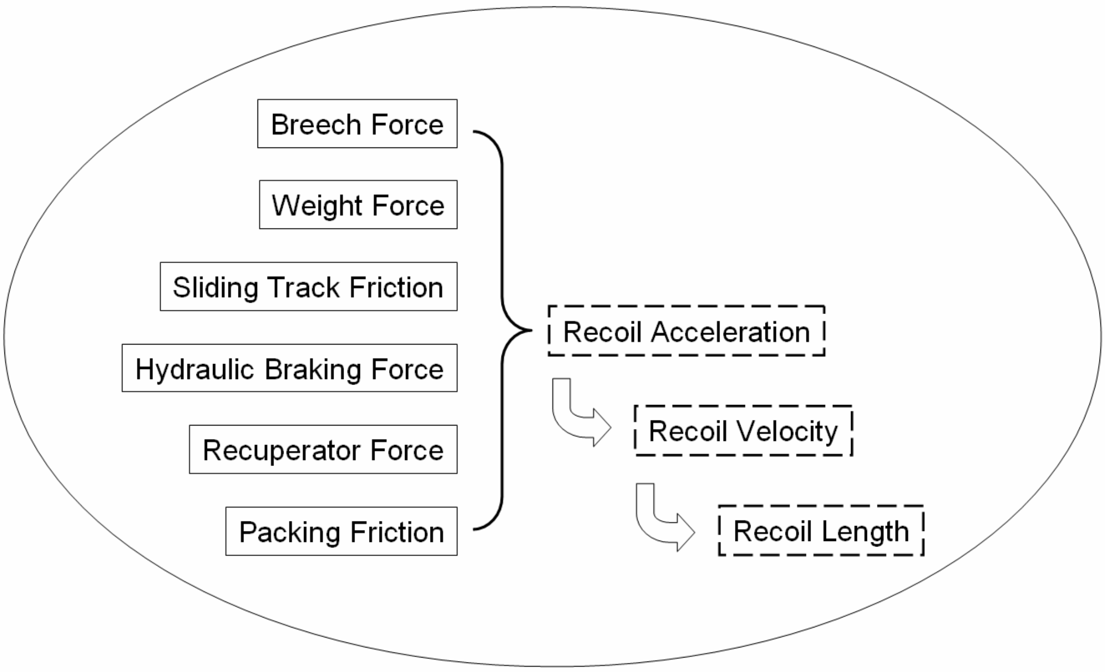


Figure 4.3-12 Flowchart of modules combination

CHAPTER 5

DYNAMIC SIMULATION AND OPTIMIZATION

5.1 Introduction

In this chapter, the dynamic models of individual components and overall system created in CHPATER 4 will be simulated and analyzed. Because there is no experiment data available at this moment, the simulation results are verified with previous studies and qualitative analyses. The assumptions proposed in previous sections are confirmed again to make sure the simulation results will be reasonable. The effects of individual parameters on the recoil mechanism are discussed in section 5.2, and optimization of the entire model is introduced in section 5.3.

Design objective of the recoil mechanism is to decrease the maximum recoil length. After the main forces, the breech force, the hydraulic braking force, and the recuperator force, are combined, the recoil length is expected to decrease during the recoil time within $0.14 sec$.

5.2 Dynamic Simulation and Results

5.2.1 Simulation Assumptions

In this study, there are some assumptions supposed. Before simulation, these assumptions have to be defined. The detail descriptions on these assumptions are mentioned in section 3.1 and 3.5.5. Most important of all, the fluids including oil and air are assumed to be incompressible.

5.2.2 Simulation of Recoil Mechanism

The relations of breech force and projectile velocity versus projectile travel are shown in Figure 5.2-1 and Figure 5.2-2. In bore period, the time only retains $0.0123 sec$. The input value of breech force versus time is shown in Figure 5.2-3. When the projectile travel is up to $200 in$, the projectile exits the muzzle. At this moment, the breech force still exists. After exiting the muzzle, the force decreases to zero gradually. Because there is no muzzle brake in this model, the breech force is not changed from positive to negative value as the projectile exits the muzzle.

Simulation result of the recoil mechanism model is shown in Figure 5.2-4. The relation is between recoil acceleration and time. Because no muzzle brake exists, the moment of negative recoil acceleration occurs later than the system with a muzzle brake. Around $0.0220 sec$, the recoil acceleration is changed to negative. Thus the recoil velocity will decrease at this moment.

The recoil velocity is the integration of the recoil acceleration relative to the time, as shown in Figure 5.2-5. The maximum value happens about $0.0220 sec$. This time is the same that the recoil acceleration is changed from positive to negative. It means that the breech force is smaller than original value. After that, the recoil acceleration is changed to negative and velocity decrease gradually. Finally, the recoil velocity becomes to zero at $0.1160 sec$. The recoil travel is finished, and the counterrecoil travel will begin.

Similarly, the recoil length can be obtained by the integration of the recoil length, as shown in Figure 5.2-6. This result is for long travel simulation. The maximum displacement of recoil length happens at $0.1160 sec$. At that time, the recoil velocity is zero, and the maximum displacement is $35.8188 in$. After that, the recoil length decreases, it means that the counterrecoil travel starts.

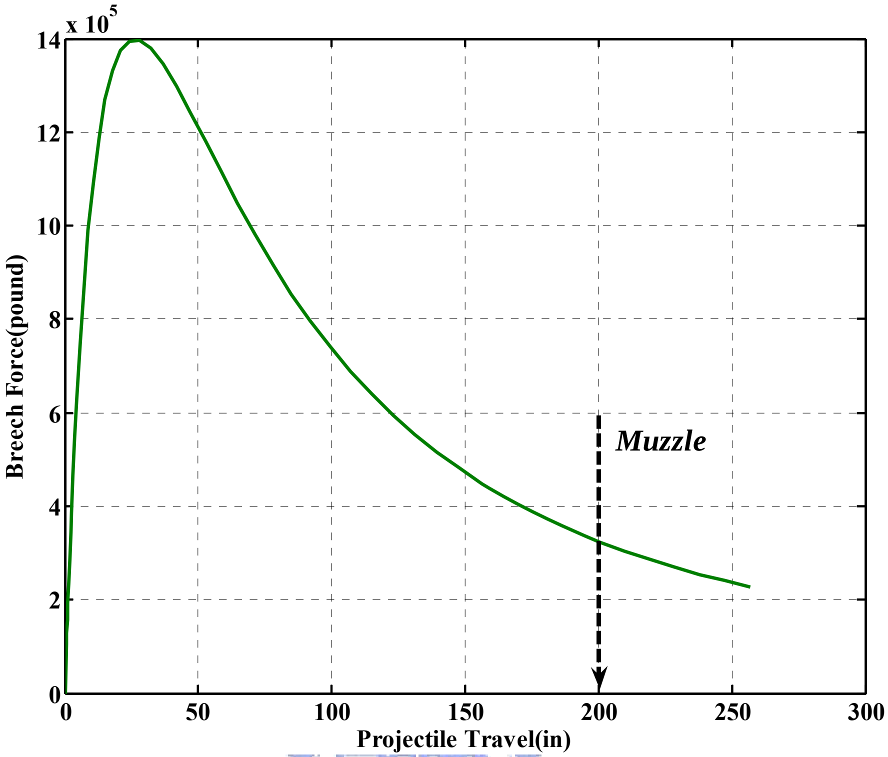


Figure 5.2-1 Breech force versus projectile travel

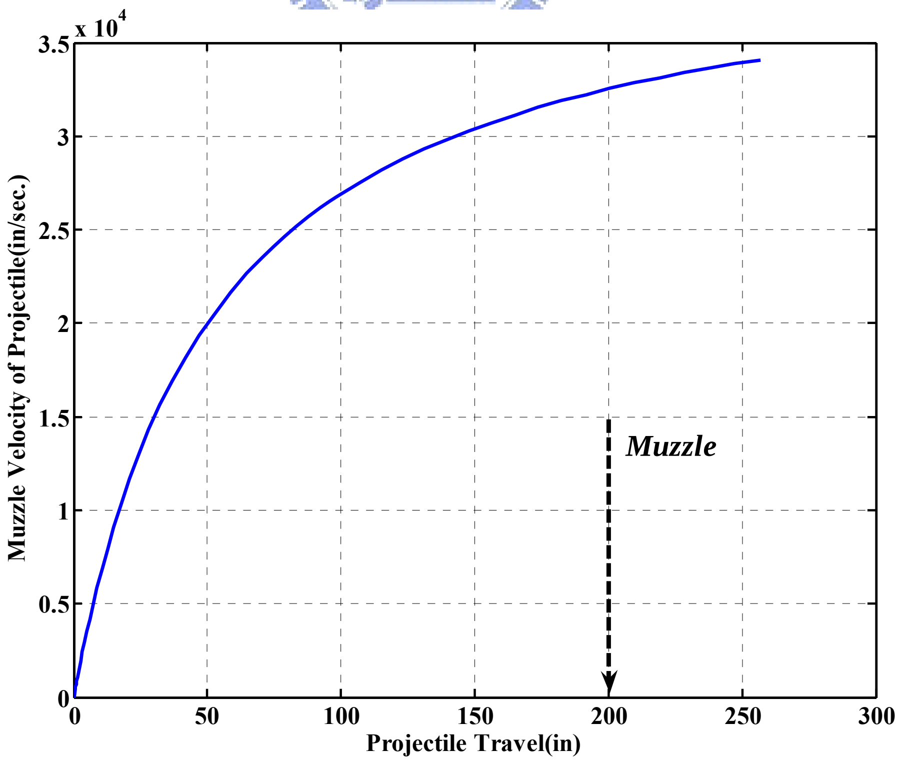


Figure 5.2-2 Projectile velocity versus projectile travel

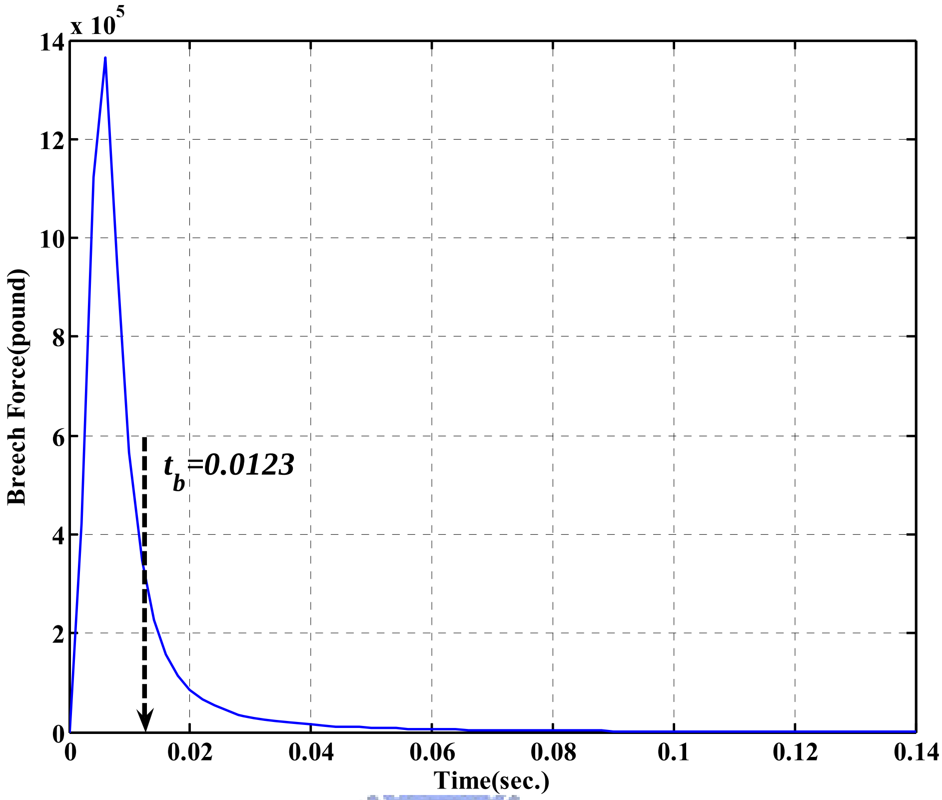


Figure 5.2-3 Breech force versus time

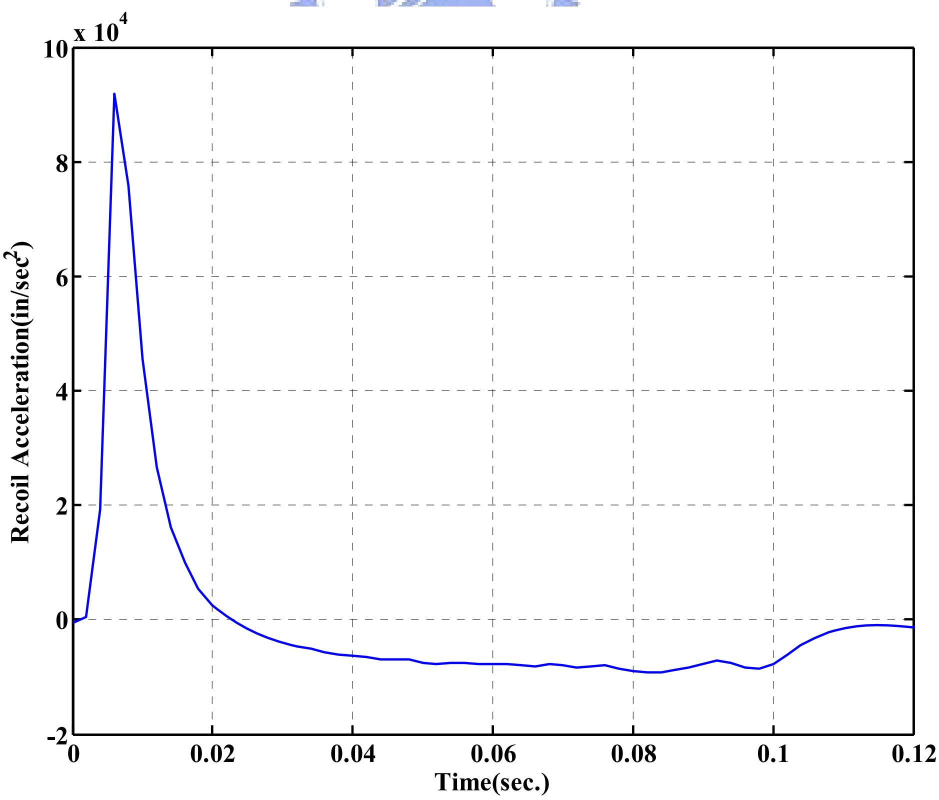


Figure 5.2-4 Recoil acceleration versus time

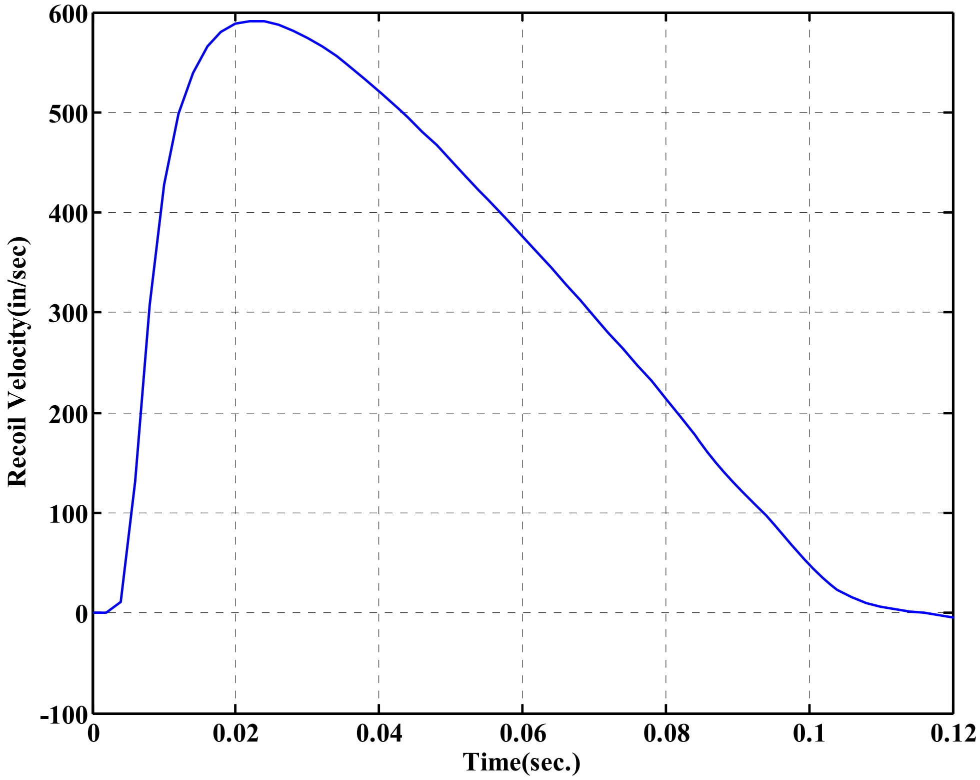


Figure 5.2-5 Recoil velocity versus time

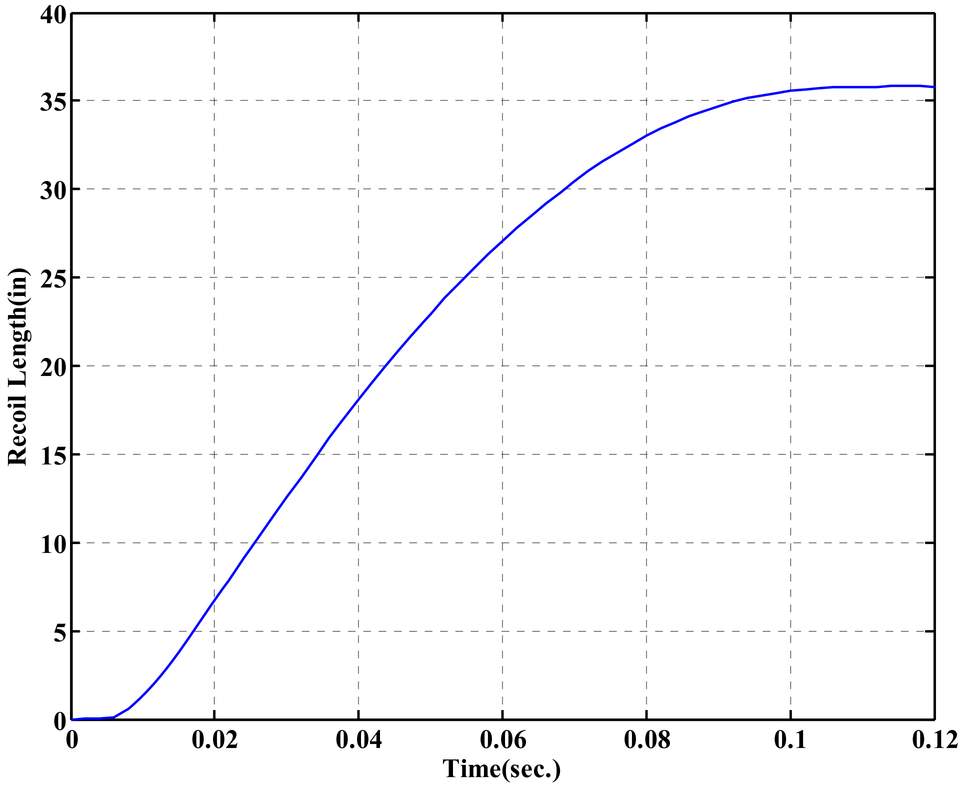


Figure 5.2-6 Recoil length versus time

5.2.3 Leakage Area

Under the original design, the relation between orifice area and recoil length is shown in Figure 5.2-7. The simulation in section 5.2.3 is made according to the original values. However, the orifice area is required to add the leakage area, as shown in Figure 5.2-7, during the action of the recoil mechanism. Therefore, the actual orifice area will be used here.

The existence of the leakage area is due to the manufacturing tolerance. When the gun stops, the recoil piston is hermetically sealed with orifice. But because of the tolerance shown in Figure 5.2-8, the leakage affect disappears after the backward movement of the recoil piston. In general design experience, the leakage area is about $0.5 in^2$, and will be constant in all the recoil travel.

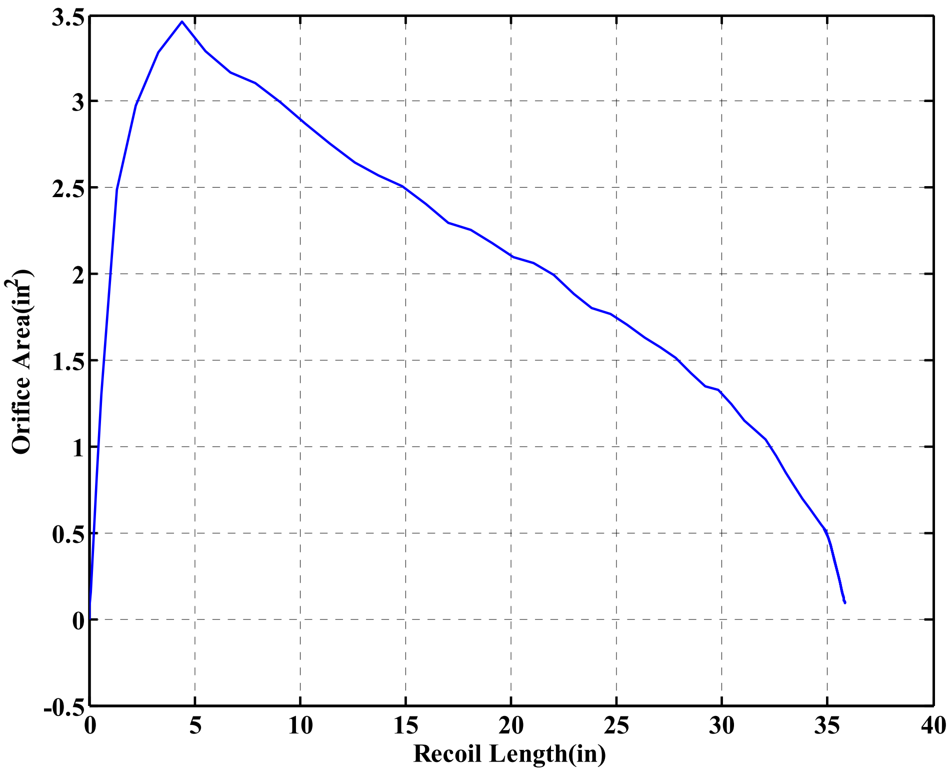


Figure 5.2-7 Orifice area versus recoil length

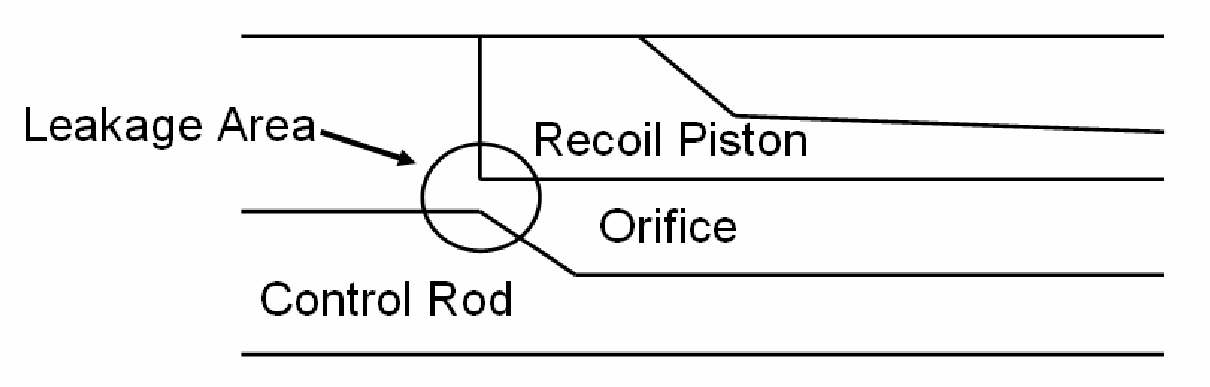


Figure 5.2-8 Diagram of leakage area

In the previous simulation, the orifice area is zero at start position and maximum displacement. But it is required to add the leakage area, and the minimum area is $0.5in^2$. In other words, if the area is smaller than $0.5in^2$, it is set to be $0.5in^2$, as shown in Figure 4.3-8.

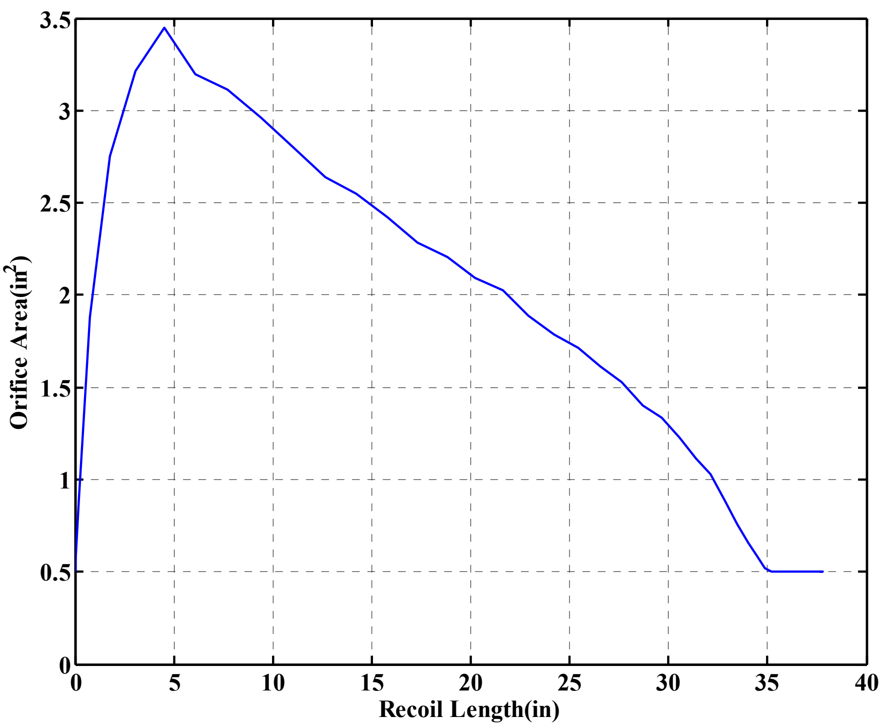


Figure 5.2-9 Orifice area versus recoil length

Because the recoil velocity is positive proportion to the orifice area, the initial recoil velocity will raise after adding leakage area if the breech force keeps constant. At the same time, the orifice area is $0.5in^2$ when recoil travel finished. It causes that the recoil length exceeds the original value. Besides, the hydraulic braking force is direct proportional to the square of recoil velocity. Hence, the addition of recoil velocity makes the hydraulic braking force increase.

After adding the leakage area, the initial values of the recoil acceleration, the recoil velocity, and the recoil length are increased. Figure 5.2-10 shows that the recoil acceleration increases after considering leakage area. And when the recoil travel is ending, there exists a large recoil acceleration making the velocity to zero.

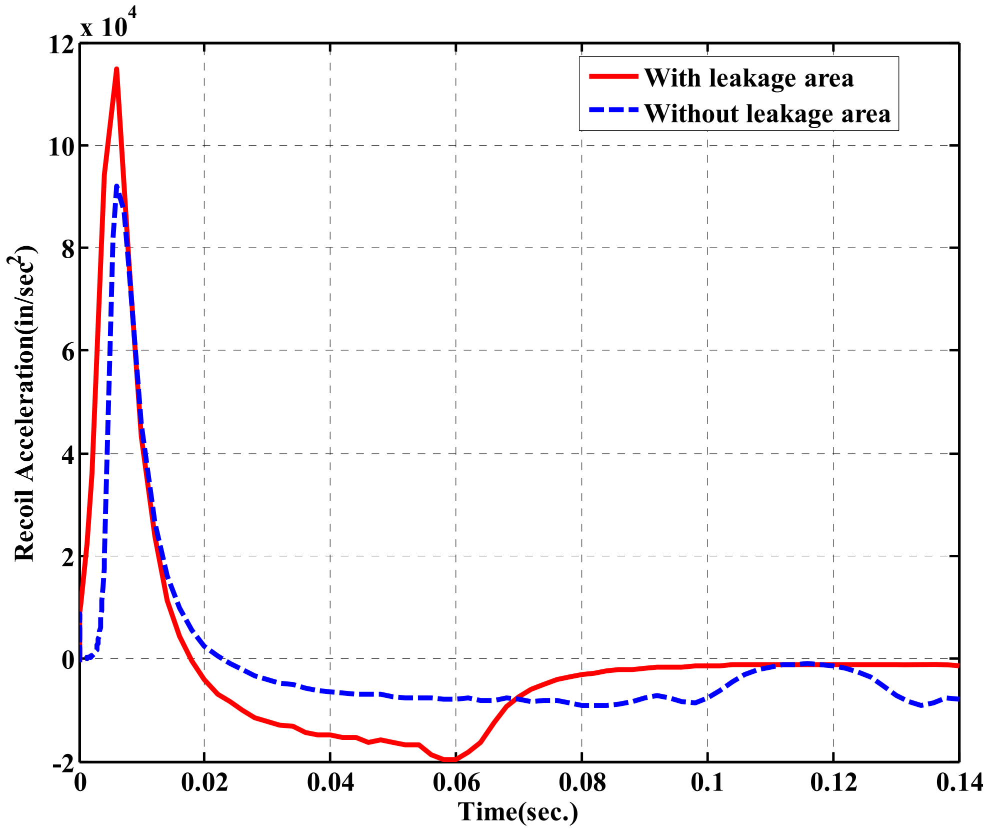


Figure 5.2-10 Recoil acceleration versus time at different leakage area

As a result of the change of the recoil acceleration, the recoil velocity also changes. The recoil velocity is direct proportional to the orifice area. And the hydraulic braking force is also direct proportional to the square of the recoil velocity. Thus, the total braking force increases. Because the orifice area cannot drop into zero when the recoil travel finishes, the moment of the recoil velocity dropping into zero is extended to $0.1220 sec$. Figure 5.2-11 is the comparison of recoil velocity when leakage area exists or not.

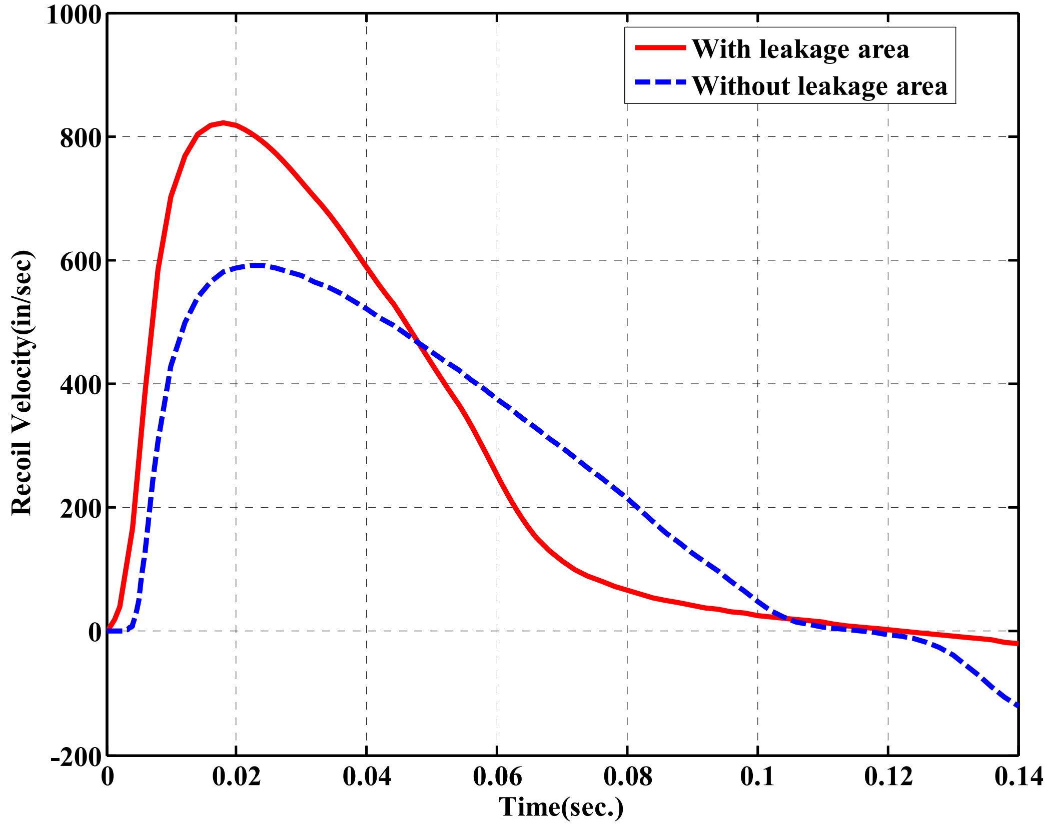


Figure 5.2-11 Recoil velocity versus time at different leakage area

Similarly, the recoil length increases because of the existence of the leakage area. However, the hydraulic braking force is an inverse proportion to the orifice area. Therefore, if the orifice area is less than $0.5 in^2$, it will set to be $0.5 in^2$ in order that the hydraulic braking force will decrease rapidly. The recoil motion can't stop at original maximum position. After joining leakage area, the time of the maximum displacement increases to

0.1220*sec*, and displacement increases to 37.7573*in*.

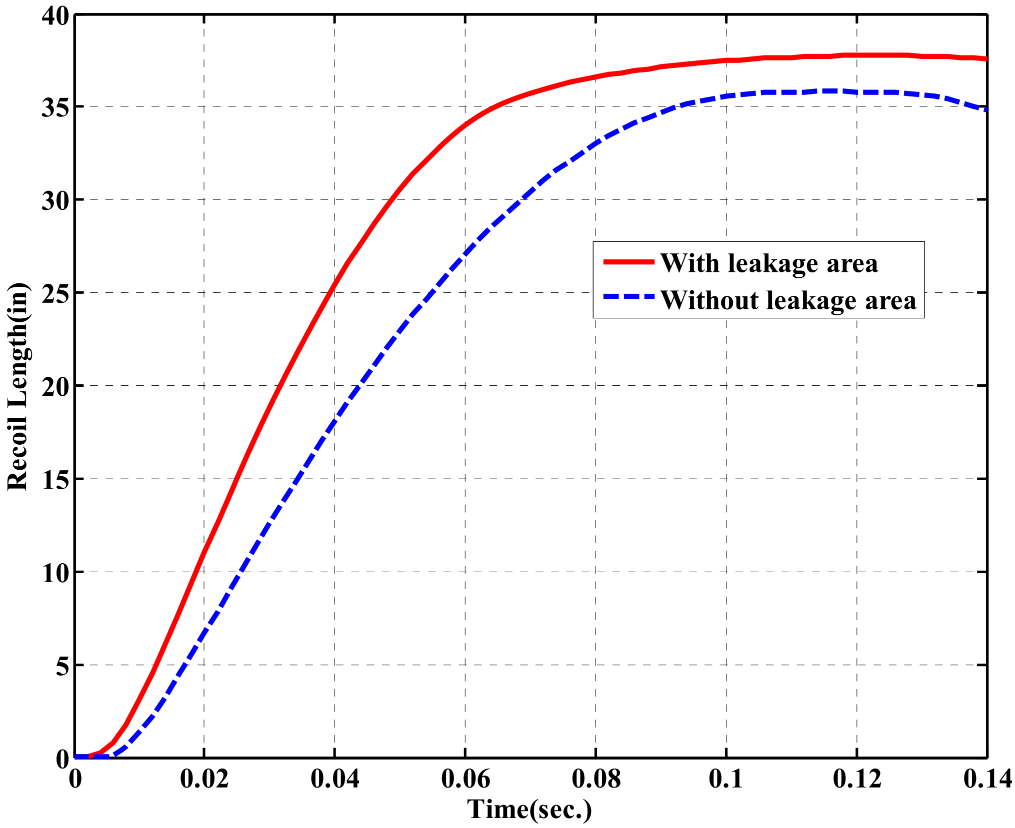


Figure 5.2-12 Recoil length versus time at different leakage area

5.2.4 Model Adequacy Checking

In this section, the simulation model is required to be confirmed that it is reasonable. Because there is no experimental data to support the simulation results, the model will be confirmed by physical analysis.

First, if the charge weight increases (more powder), the generated energy also increases. It causes bigger forward force of the projectile, and the breech force also becomes bigger relatively. Therefore, the recoil length will increase because of the bigger breech force. The simulation model shows the result in Figure 5.2-13 and Figure 5.2-14.

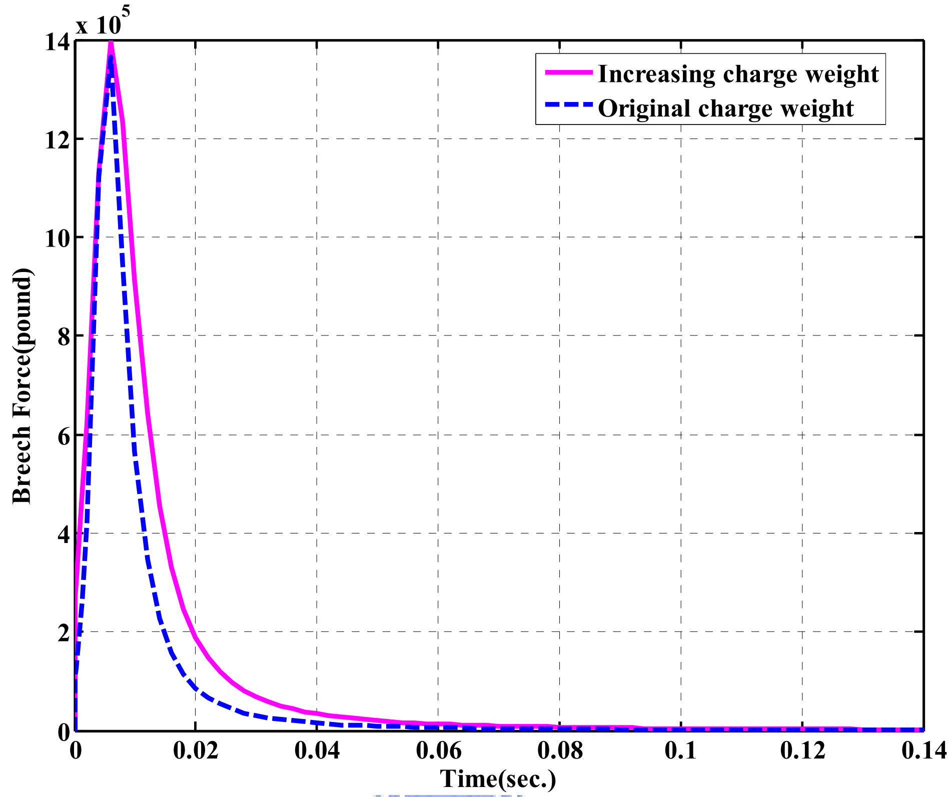


Figure 5.2-13 Breech force versus time at different charge weight

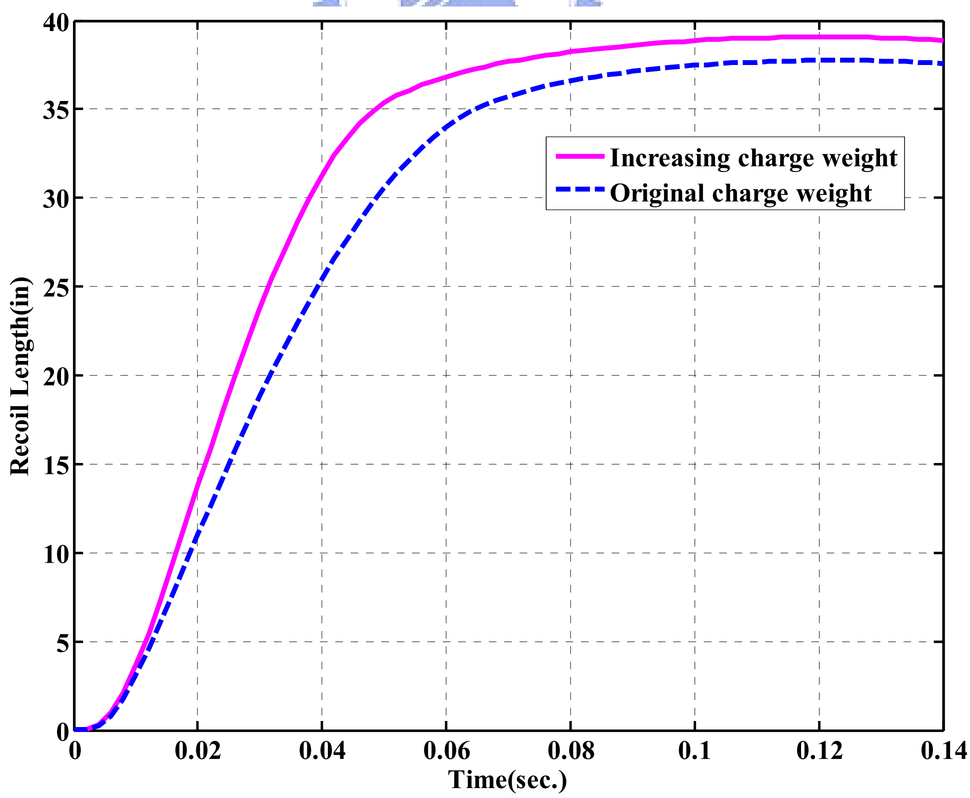


Figure 5.2-14 Recoil length versus time at different charge weight

Second, the energy generated from the charge weight will push the projectile moving forward. When projectile exits the muzzle, there is a projectile velocity generating. It calls muzzle velocity of projectile. If muzzle velocity of projectile is faster, it means the forward force is bigger. And it also increases breech force. Therefore, the recoil length will increase because of the bigger breech force. Figure 5.2-15 and Figure 5.2-16 show this phenomenon.

The above mentioned is a simple principle to confirm the model adequacy, and the property of each parameter can be explained by physical phenomenon. The tendency is reasonable and correct. Then, the optimization method can be performed in the following section.

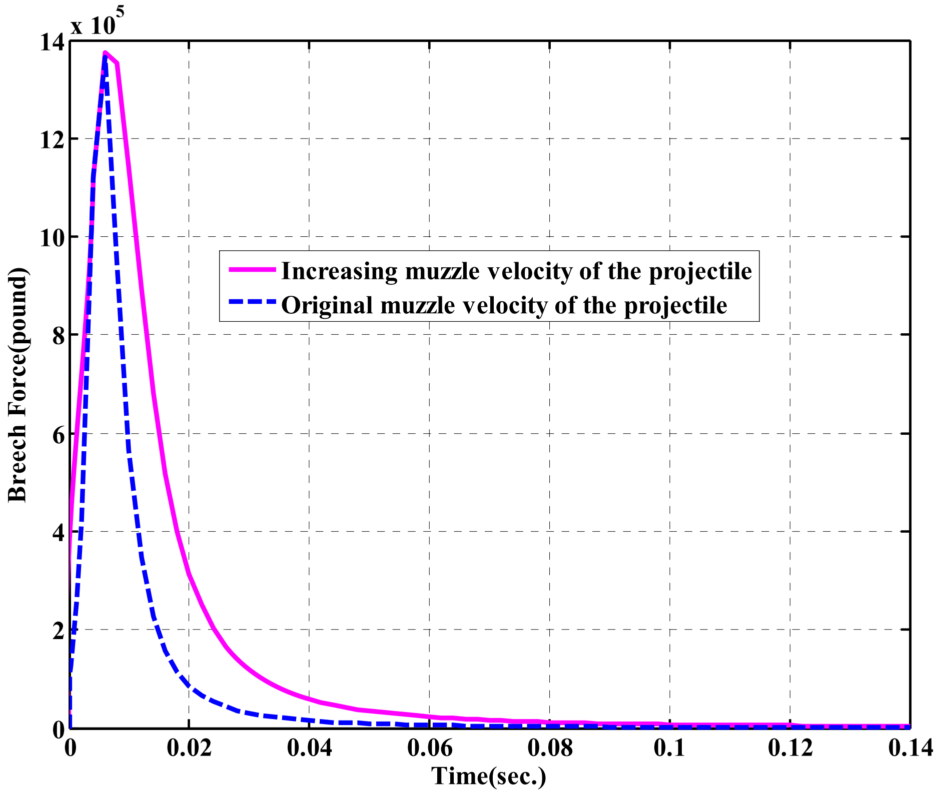


Figure 5.2-15 Breech force versus time at different muzzle velocity

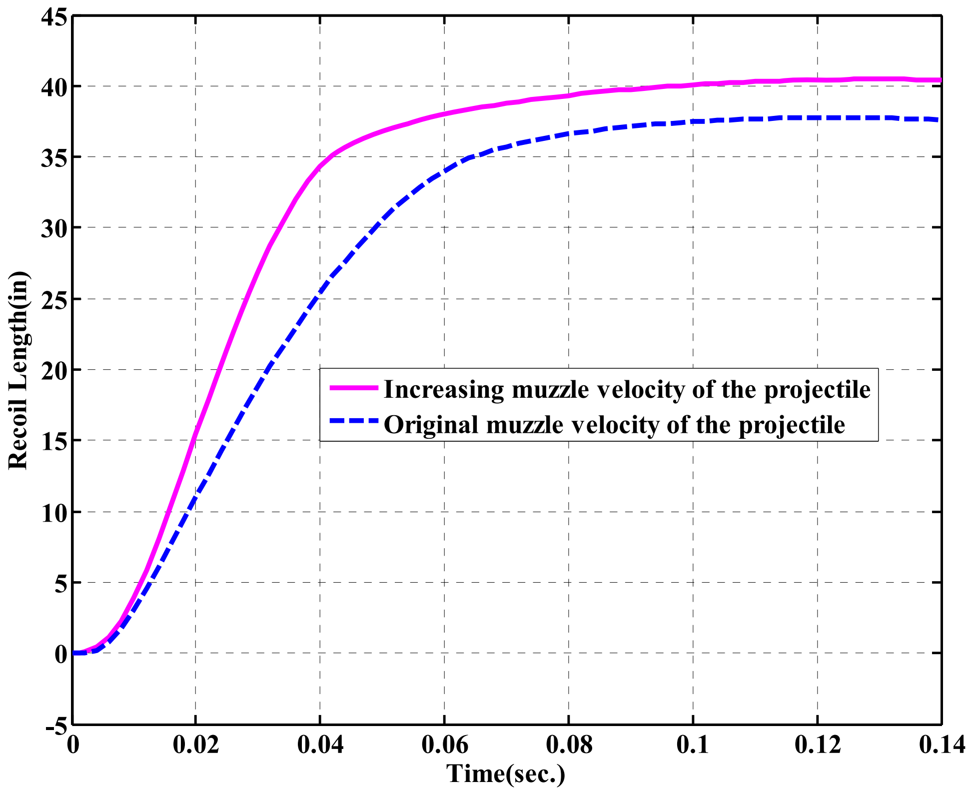


Figure 5.2-16 Recoil length versus time at different muzzle velocity

5.3 Optimization

In this section, the recoil mechanism is optimized to get a shorter recoil length. In the following subsections, cost function, design variables, and constraints are defined according to the foregoing objective. Finally, optimization is executed.

5.3.1 Sensitivity Analysis

The recoil length will change when related variables are altered. The benefit of sensitivity analysis can investigate how the variables affect the recoil length, and Figure 5.3-1 and Figure 5.3-2 show the results. In Figure 5.3-1 and Figure 5.3-2, the percentage of variable change is from 0% to 100% in the X-axis and the change of maximum recoil length is in Y-axis. Eight geometrical parameters are investigated in this sensitivity analysis. Originally, there are many parameters in this mechanism. But maximum bore pressure, muzzle velocity of the projectile, and charge weight force are determined by specific kind of ammunition. Therefore, these parameters seldom change. And the recuperator usually uses the nitrogen gas, and its polytropic exponent is fixed. Because of these reasons, there are only eight parameters suitable to do sensitivity analysis to decide the more influenced parameters on the maximum recoil length.

Each parameter has its reasonable range, and the comparative standard regards as the same percentage of the variable range as shown in Table 5.3-1. Although many parameters influence the recoil length, the sensitivity analysis only considers one parameter change at a time.

Table 5.3-1 The range of parameters

Description	**Unit**	**Notation**	**Range**
Effective area of the recoil piston	in^2	A	$29.6784 \sim 36.2736 in^2$
Bore area	in^2	A_b	$29.4525 \sim 30.0475 in^2$
Effective area of the recuperating cylinder	in^2	A_R	$8.7516 \sim 10.6964 in^2$
Recuperator gas pressure in battery	psi	Pi	$585 \sim 715 psi$
Barrel length	in	U_0	$140 \sim 260 in$
Recuperator gas volume in battery	in^3	Vi	$913.5 \sim 1116.5 in^3$
Projectile weight force	lb	W_P	$90 \sim 140 lb$
Density of fluid	lb/in^3	ω	$0.030845 \sim 0.031815 lb/in^3$

In Figure 5.3-1, it can be seen that there are three sensitive factors influencing the maximum recoil length: the effective area of the recoil piston A, the barrel length U_0, and the projectile weight force W_P. Effective area of the recoil piston, and barrel length are negatively correlated with the maximum recoil length. And projectile weight force is positively correlated with the maximum recoil length. Other five parameters are not obvious in this figure.

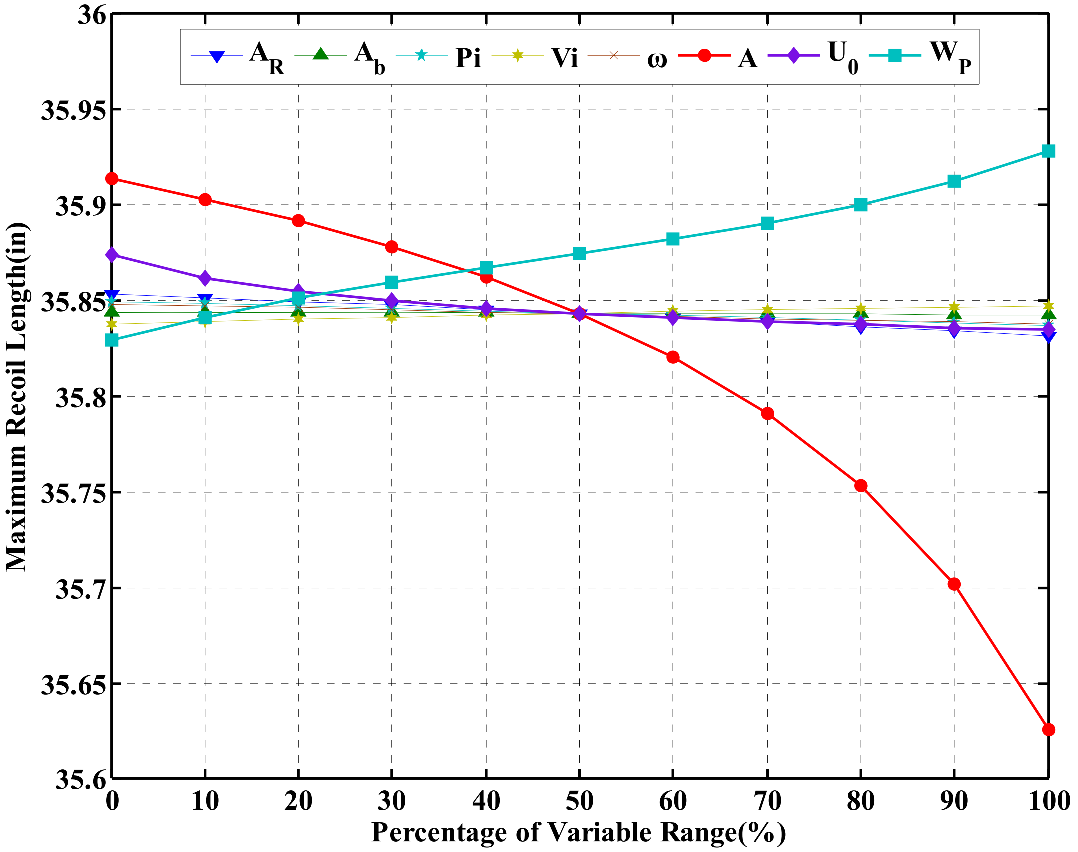


Figure 5.3-1 Sensitivity analysis of all variables

Figure 5.3-2 shows the changes of the five parameters in a larger scale. Effective area of the recuperating cylinder is the most sensitive factor which is negatively correlated with the maximum recoil length. The other four parameters are slight sensitivity in the results.

According to the above discussion, there are four most sensitive parameters treated as design variables in optimization, the effective area of the recoil piston A, the barrel length

U_0, the projectile weight force W_P, and the effective area of the recuperating cylinder A_R.

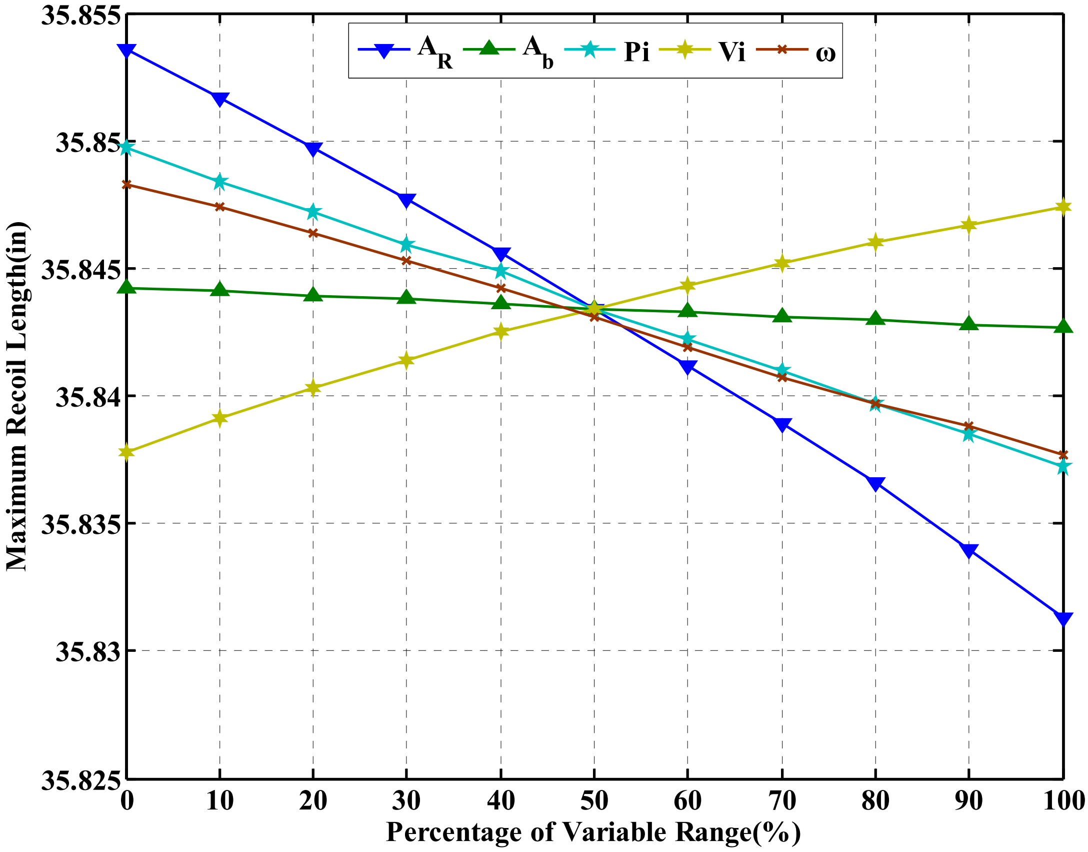


Figure 5.3-2 Sensitivity analysis of partial variables

5.3.2 Cost Function

After the model construction of the recoil mechanism, this section uses this model to perform optimization. Large recoil distance is the most important problem that hinders from designing the space requirement of other mechanisms. Therefore, optimization will focus on how to reduce the maximum recoil length. Therefore, the maximum recoil length of the recoil mechanism which is needed to be minimized is defined as the cost function of the optimization problem.

5.3.3 Design Variables

All parameters in the model are listed in Table 4.3-4 and Table 4.3-5, and the influences of these parameters on cost function are discussed in Section 5.3.1. There are four design variables: the barrel length, the projectile weight force, the effective area of the recoil piston, and the effective area of the recuperating cylinder.

The first variable, barrel length, is the geometrical parameter from the recoiling parts. The barrel length affects the value of the breech force. Since the artillery has different length of barrel, adjustment of barrel length most modifies the required breech force.

The second variable, the projectile weight force, is the weight of the projectile. It also affects the value of breech force. Since the artillery has different weight of projectile, adjustment of the projectile weight can control the required breech force. The design value can be adjusted as long as the gunshot is still satisfied.

The third variable, the effective area of the recoil piston, is the geometrical parameter from the recoil brake. Effective area of the recoil piston affects the value of hydraulic braking force. It affects the total braking force indirectly. And it provides negative relation of recoil length.

The fourth variable, the effective area of the recuperating cylinder, is the geometrical parameter from the recuperator. Effective area of the recoil piston affects the value of recuperator force. Although it doesn't affect the recoil length too much, it is still improved to find a better design on the recoil length.

The design variables are listed in Table 5.3-2.

Table 5.3-2 Design variables

Design Variables	**Unit**	**Notation**	**Component**
Barrel length	*in*	U_0	Recoil parts
Projectile weight force	*lb*	W_P	Recoil parts
Effective area of the recoil piston	in^2	A	Recoil brake
Effective area of the recuperating cylinder	in^2	A_R	Recuperator

5.3.4 Constraints

In order to avoid unimplemented optimization result, some constraints are defined in this subsection. First, since the cost function of the optimization is to minimize the maximum recoil length, improper parameter setting may cause the optimization results impracticable. Thus, it needs some suitable range to constraint the geometrical parameters in the mechanism. And the range of design variables is listed in Table 5.3-1.

5.3.5 Optimization Results

According to the definitions in previous subsections, optimization of the mechanical structure of the recoil mechanism is executed by using Matlab®.

In this study, optimization Toolbox Matlab® is used to solve the problem. Since the optimization problem is defined as a nonlinear constrained multivariable problem, “fmincon”, which is used to find a minimum of a constrained multivariable function, is chosen to solve the problem.

The function “fmincon” deals with the constrained problem using Sequential Quadratic Programming (SQP) method [15]. SQP method uses Kuhn-Tucker (KT) equation as basis.

SQP method attempts to compute the Lagrange multiplier directly. Constrained quasi-Newton method guarantees super linear convergence by accumulating second order information regarding the KT equations using quasi-Newton updating procedure [14].

There are three main stages to implement SQP method. The first is updating of the Hessian matrix. At each major iteration, a positive definite quasi-Newton approximation of the Hessian of the Lagrangian function is calculated that is using BFGS (Broyden-Fletcher-Goldfarb-Shanno) method. The second is to compute Quadratic Programming QP solution. At each major iteration, a QP problem, which is a sub problem generated from Hessian of the Lagrangian function calculated before, is solved, and the solution is used to form a search direction for a line search procedure. The third is line search and merit function calculation. Using the search direction produced in QP problem, a step length which is sufficient to decrease a merit function is determined, where the merit function is in the form defined by Han [16] and Powell [14] [17].

Using "fmincon" as the implement program, and combining the dynamic model built in Simulink® as cost function, the optimization results can be obtained as follows.

From Table 5.3-3 and Figure 5.3-3, it is obviously that the maximum recoil distance is reduced from $37.7573in$ to $35.9117in$. It decreases $1.8456in$ (about 4.89%) from the original length. And from the results of optimization, all design variables go on the boundary of the variable range. It is because there are no extra constraints to limit the magnitude of each force expect the variable boundary.

Table 5.3-3 Optimization results

Design Variables	**Initial Design**	**Optimum Results**
Barrel length U_0	200*in*	260*in*
Projectile weight force W_P	96*lb*	90*lb*
Effective area of the recoil piston A	$32.976in^2$	$36.2736in^2$
Effective area of the recuperating cylinder A_R	$9.724in^2$	$10.6964in^2$
Cost Function X_{max} (recoil length)	37.7573*in*	35.9117*in*
Corresponding Time	0.1220 sec	0.1260 sec

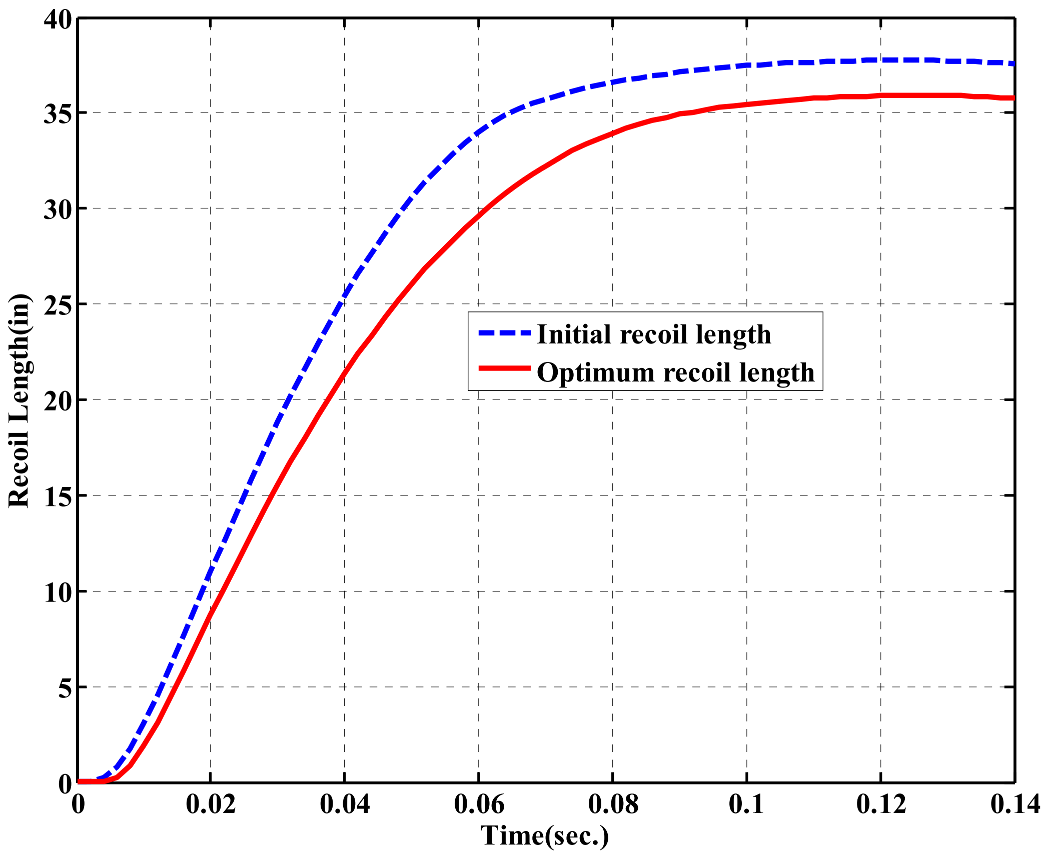


Figure 5.3-3 Optimization result

5.4 Remarks

1. The simulation of the dynamic model shows that the maximum recoil length can be computed specifically. Under different conditions, there are changes on the recoil length.

2. The tendency of the model is reasonable from physical meanings.

3. Before optimization, design variables can be determined by the sensitivity analysis. It can not only figure out the properties of all parameters, but also reduce the computation on optimization. Because too many design variables are not necessary for optimization or mechanism design.

4. After deciding the cost function, design variables, and constraints, optimization is applied. And optimum result can be obtained.

5. By adjusting the simple design variables, the maximum recoil length can be reduced. This phenomenon can make the recoil mechanism design simpler.

CHAPTER 6

DYNAMIC CONTROL OF THE ORIFICE AREA

6.1 Introduction

In this chapter, the importance of the orifice area is studied. In previous chapters, the orifice area is a pre-determined parameter. But it is better to design an ideal one according to the total braking force. But, the total braking force is difficult to keep constant in fact; the curve of the force will be treated as an ideal trapezoid, like Figure 3.4-1.

Figure 6.1-1 shows the main ideal of this chapter. When total braking force $K(t)$ is determined, the original recoil mechanism has been redesigned to meet the objective. That is, the change of orifice area versus recoil travel and time must be found by importing the different elevation and the recoil length. Therefore, control methods can make the change of the orifice area fill the bill.

In order to find the relation between orifice area and elevation, the new model is created. Besides, the model will be simulated and analyzed later. Finally, the concepts of controlling the orifice area will be discussed.

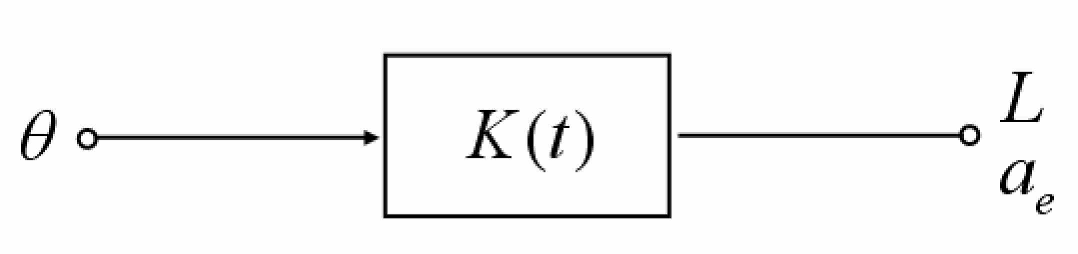


Figure 6.1-1 Block diagram for control orifice area

6.2 Model Creation

Figure 6.2-1 shows the logic flow of controlling the orifice area. It is different form Figure 4.3-12. Here, the curve of the total braking force is designed as an ideal trapezoid, and it can be determined by experiments in real applications. Other force components like the packing friction, the recuperator force, and the hydraulic braking force are calculated in successive. Then the orifice area versus recoil travel and time can be found by the known hydraulic braking force.

The dynamic equations of the total braking force can be form at section 3.4. And the other forces are as same as the foregoing model. The combined system is shown in Figure 6.2-2.

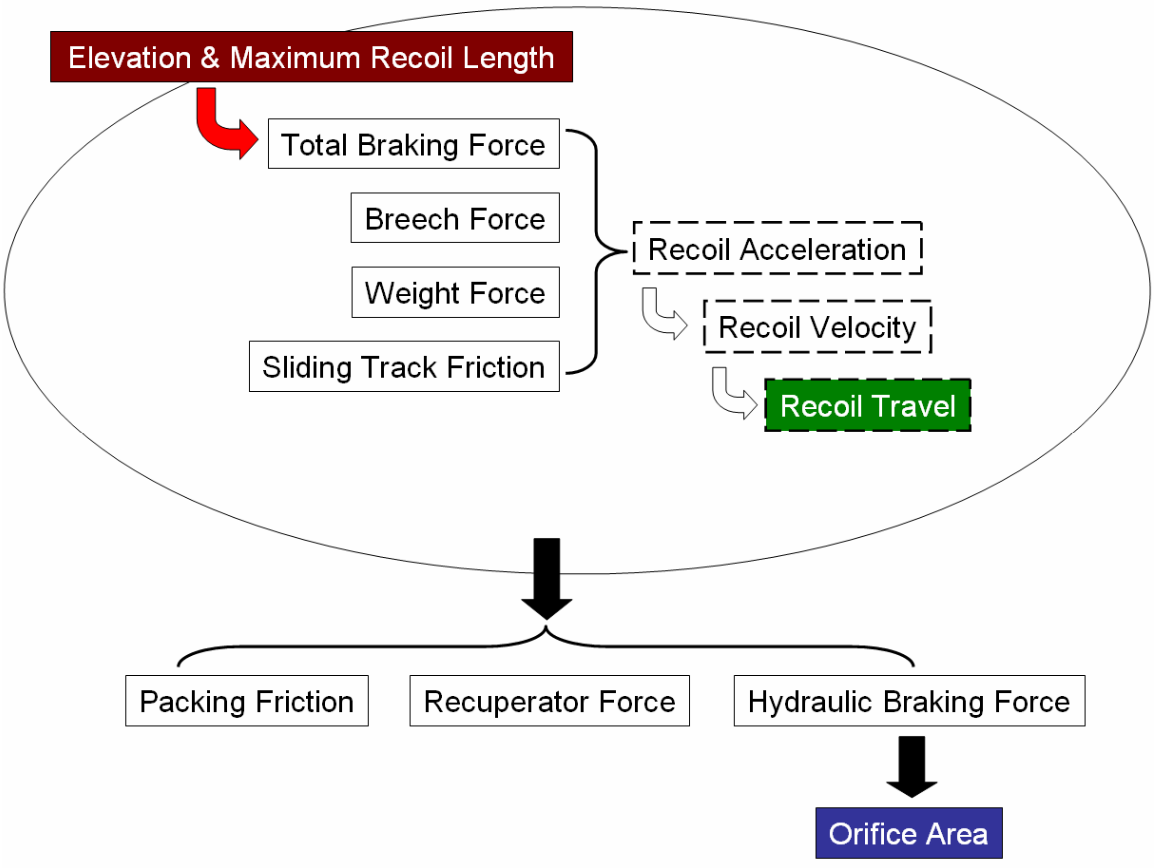


Figure 6.2-1 Flowchart of modules combination

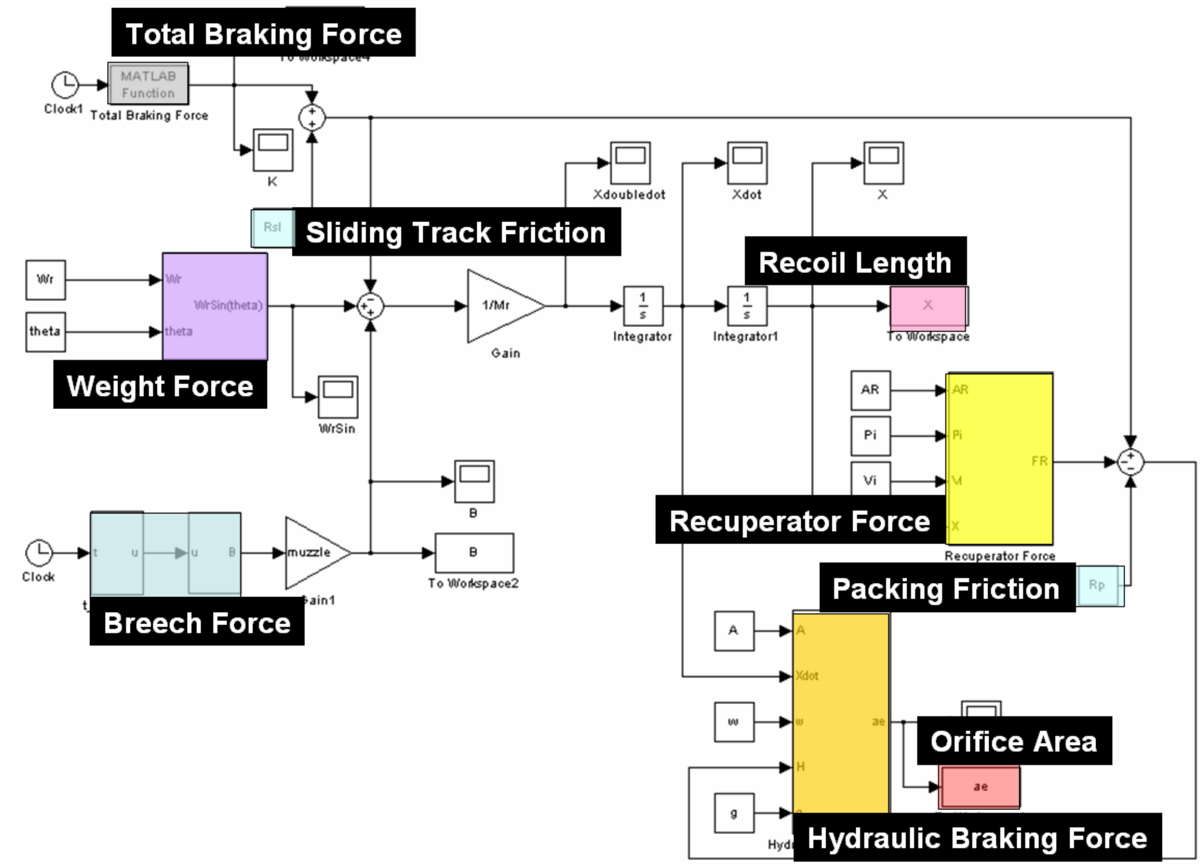


Figure 6.2-2 Combined system model of the recoil mechanism

6.3 Dynamic Simulation and Results

The relation between the orifice area and time is shown in Figure 6.3-1. The real line with low elevation is stopped at $0.0864 sec$. The other virtual line with high elevation is stopped at $0.0636 sec$. The results show that high elevation causes the change of the orifice area faster. Besides, the relation of orifice area versus recoil travel is shown in Figure 6.3-2. In the same way, because there is less space, the high elevation causes shorter recoil length. With the two figures, the changes of orifice area versus time or recoil travel at different elevation can be known. And if the orifice area can be controlled according to the curves, the efficiency of the recoil mechanism will be better than before.

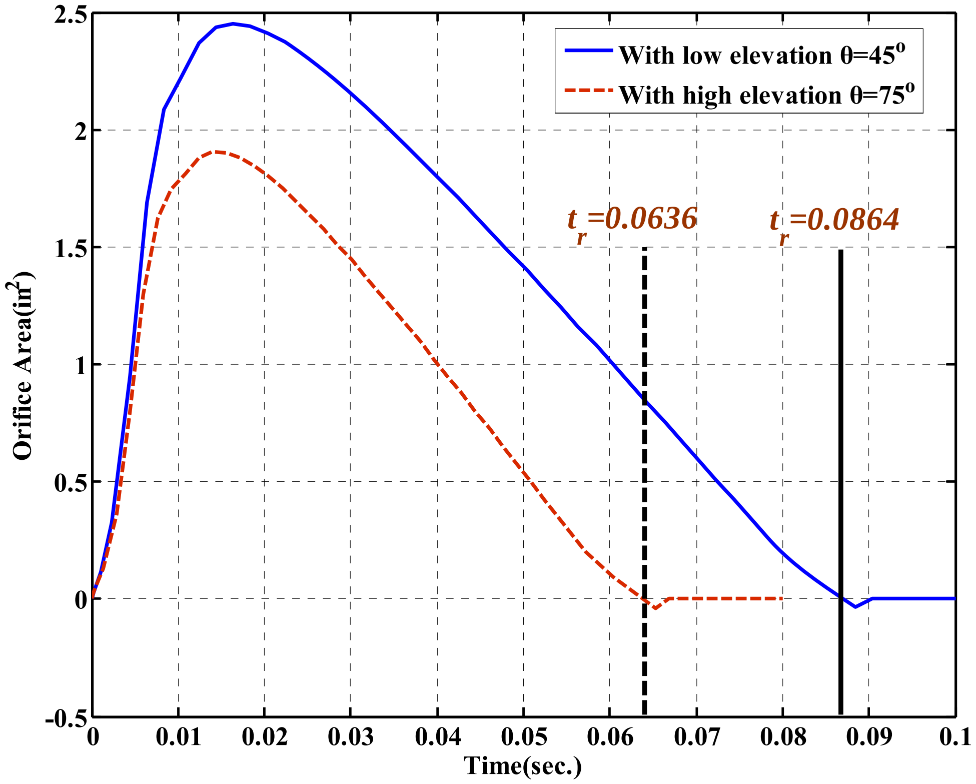


Figure 6.3-1 Orifice area versus time at different elevation

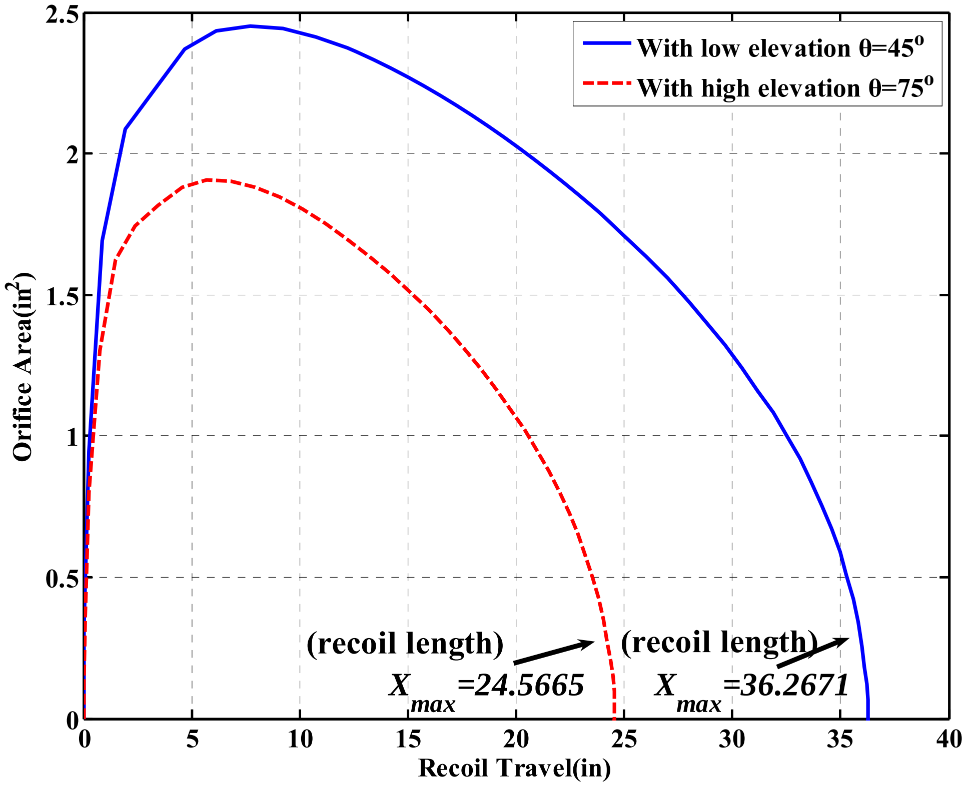


Figure 6.3-2 Orifice area versus recoil travel at different elevation

Figure 6.3-3 shows the 3D curves of orifice area versus recoil travel at different elevation from thirty degrees to seventy-five degrees. Figure 6.3-4 and Figure 6.3-5 show the surface plots of the orifice area versus the recoil travel and the orifice area versus time at different elevation. And from these figures, the tendency states that the orifice area will shrink faster when the elevation is higher and higher.

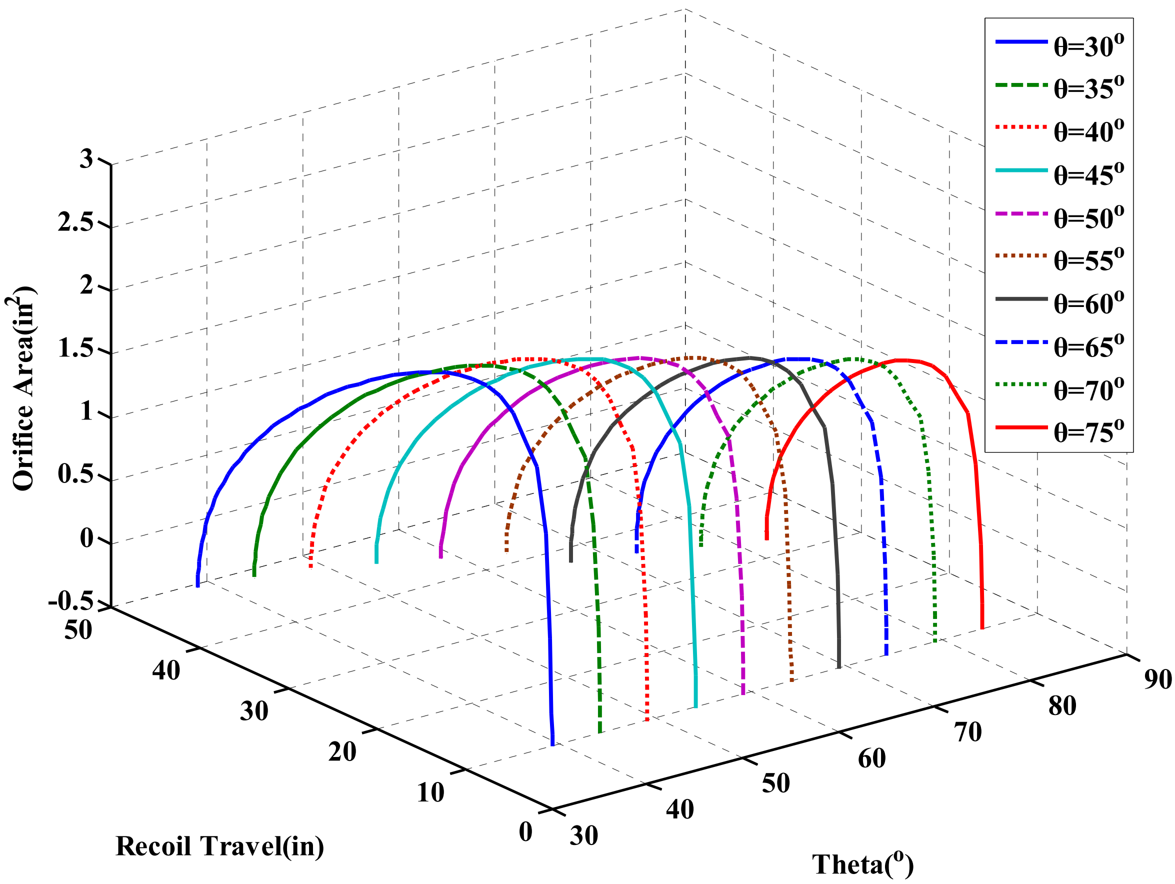


Figure 6.3-3 3D curves at different elevation

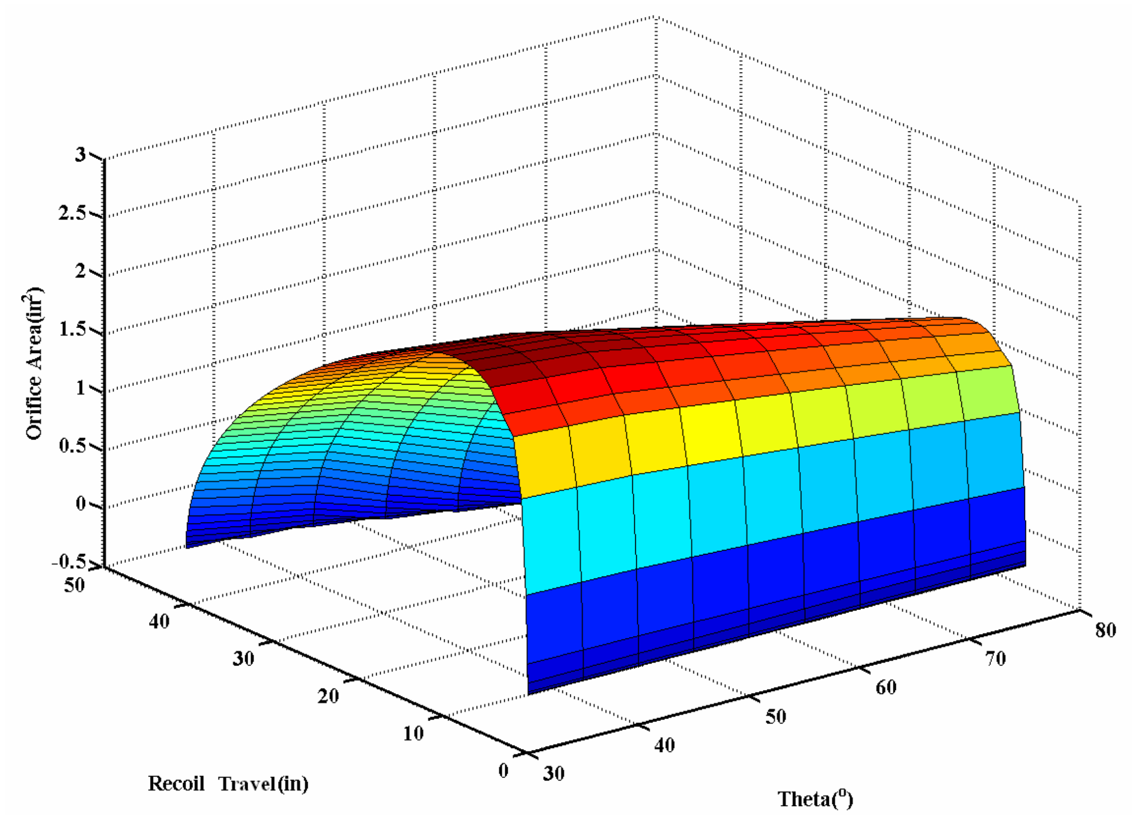


Figure 6.3-4 Surface plot of the orifice area versus recoil travel at different elevation

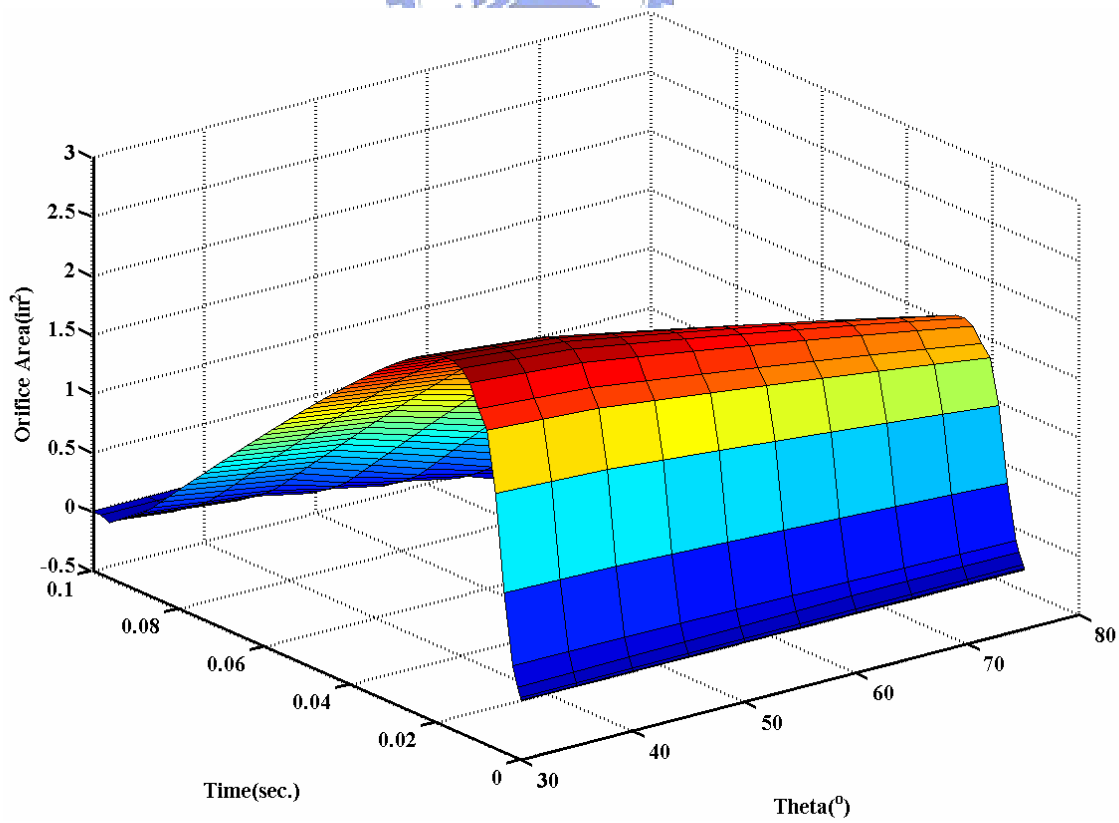


Figure 6.3-5 Surface plot of the orifice area versus time at different elevation

6.4 Discussions

From the simulation results, it is obvious that the desired orifice areas vary according to the recoil travel and time. Therefore, the design of the orifice area is the most important parameter to control the total braking force. Through the study of this chapter, the relation of the orifice area versus recoil travel and time at different elevation can be known.

Traditionally, designers usually designed the structure to cater to the change of the orifice area in the recoil mechanism. But in the present, there are so many electrical and mechanical control methods and apparatus which can get the goal. By integrating sensors and actuators, environmental situation can be obtained easily and input to a control center. The desired orifice area can be found, and the actuator can work according to the calculated output. This control method can increase the efficiency of the recoil mechanism, and keep the recoil length (maximum recoil travel) in a desired distance. As mentioned before, it is very important when firing at a high elevation, and also important when designing the vehicular application.

CHAPTER 7

CONCLUSIONS AND FURTHER WORKS

7.1 Conclusions

Owing to the advancement of military views and scientific techniques, all countries in the world do their best to develop the war industry. One of the most important things is the development of guns, which are the backbone of the ground protection. A recoil mechanism can reduce the mass recoil force during firing, and push the gun body back to the original position after firing. Because the recoil mechanism was invented, the gun performance got unprecedented improvement. Therefore, the purpose of this research is to find a mathematical model for the recoil force, and it can be implemented by computer program for simulation. The results can provide a clear understanding for designing the mechanism or improving the performance of recoil ability. And some conclusions can be made as follows:

1. On the recoil mechanism, all forces and important parameters are listed clearly. A complete and reliable mathematical model of the recoil mechanism is obtained. Up to the present, there is less information on the complete description of the recoil mechanism. Before analyzing or designing, it can check the theory and the mathematical model. The proposed checking process ensures that the product can be designed correctly according to the original information.

2. The dynamic model can be built by Simulink® instinctively, and has different combinations under different hypothesis. It is very flexible. Besides, the simulation of the dynamic model shows that the maximum recoil length can be computed specifically. Under different conditions, there are changes on the recoil length. It means

that the simulation result predicts the changes of recoil length. It can save the cost to do many real experiments. Furthermore, the maximum recoil length is improved by adjusting the simple design variables. And it makes the space of the artillery use effectively.

3. In fact, the orifice area is also important to the maximum recoil length. So the concept to control the change of the orifice area is a subject. After understanding the relation between orifice area versus time and orifice area versus recoil travel, the control method is generated. By controlling the orifice area, the maximum recoil length can also reduce to meet the objective.

7.2 Future Works

In the future works of this study, some points can be focused on as listed below.

1. There are two equipments which can absorb the breech force. One is the recoil mechanism, and the other is the muzzle brake. In this study, the muzzle brake is ignored. But if it can be considered, the mathematical model of recoil mechanism can become more complete, and the model can be close to the real condition.

2. All the results in the study are not absolute results. Most of the data in this study are theoretical and some hypotheses are supposed. Modifications with experiments are necessary for providing a set of practical results and confirming the hypotheses.

3. The artillery will combine not only mechanism but also electrical parts. So how to use control methods or tools to change the change of orifice area can be studied.

4. The landing gear is similar to the recoil mechanism. The working principle is to disappear the fairly big momentum in a very short time. And the controlling method

also can make the launching and landing of an airplane smoothly.

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