

The Designer's Dilemma – Recoil: What to do with it?

William T. Zepp

Armaments Engineering & Technology Center

AMSRD-AAR-AEW-S

Picatinny Arsenal, NJ USA 07806-5000

wzepp@pica.army.mil

ABSTRACT

In the process for the design and development of cannon launched artillery weapon systems, the reaction to the barrel created by the combustion, expansion and discharge of the propellant and the interaction of the projectile must be accommodated by the weapon system within the proscribed system constraints. This reaction causes the weapon system to recoil in the opposite direction of projectile flight. This paper discusses how the system designer is constrained by both physics and the user's wishes and how the physical and system requirements are interrelated.

Presented first is a summary of recent trends in tube artillery system requirements/characteristics and long known physics that constrain any handling of the recoil. The system requirements dictated by the user include how a system is to be used and its attributes. These attributes are now focused on longer ranges, greater lethality and greater system availability. Typically, the objective is to achieve the same or greater effects on the battlefield with fewer systems. Also, the drive for greater tactical and strategic mobility of the weapon system is stressed. At the same time, the weapon system is constrained to operate and react under Newtonian mechanics. The conservation of force, momentum and energy must be maintained. Secondly, available options to the designer for the management of recoil dissipation are traded off with other system requirements. For a given recoil reaction, the designer will want to minimize the structural requirements and dynamics of the weapon system to meet other systems requirements. To do this, the force generated to counter the recoil reaction is minimized. This is accomplished by either lengthening the distance/time the recoil force is applied or by reducing the net momentum impulse applied to the system by the recoil reaction. The momentum impulse reduction can be accomplished by either imparting a momentum impulse to the barrel prior to weapon firing, or by deflecting part of the propellant gas flow out of the barrel, once the projectile exits, thus generating a forward force to the barrel. However, longer recoil distance requires a larger volume be kept clear behind the recoiling parts to accommodate the movement of these parts. This can conflict in an armoured self-propelled system with size and weight constraints that are directly affected by internal volume. The system complexity directly affects and can drive subsystem reliability and system availability requirements. The extent of propellant gas deflection directly affects not only the amount of forward force generated, but also the blast over pressure field generated by the gas discharge.

Finally, a systematic approach is outlined to handle this dilemma. Trade-offs are used to adjust required and interrelated weapon system characteristics that are directly at odds with each other on the subsystem level to obtain viable weapon system designs.

Paper presented at the RTO AVT Symposium on "Functional and Mechanical Integration of Weapons and Land and Air Vehicles", held in Williamsburg, VA, USA, 7-9 June 2004, and published in RTO-MP-AVT-108.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 JUN 2004		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE The Designers Dilemma Recoil: What to do with it?				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Armaments Engineering & Technology Center AMSRD-AAR-AEW-S Picatinny Arsenal, NJ USA 07806-5000				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM201999., The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 22	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

The Designer's Dilemma – Recoil: What to do with it?

1.0 Introduction

Since the dawn of the gunpowder age, the reaction of the weapon to the launching of the projectile has had to be dealt with. As the mass and energy of the propelling charge and the mass of the projectiles increased to achieve ever-greater range or effectiveness the weapon reaction also increased. Initially, the physical size of the weapon, the barrel in particular, required to hold the propellant gas pressures balanced or exceeded the increase in momentum imparted to the weapon. However, by the end of the 19th century, thanks in part to barrel manufacturing technology advancements in large forgings and built-up construction methods and advancements in metal cleanliness and alloy metallurgy allowing significant reduction in wall thickness with the associated weight reduction, this was no longer the case.

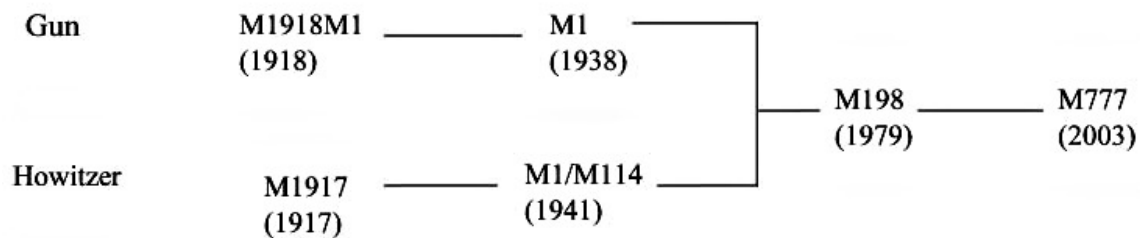
The end user, our soldiers, has continually requested improved weapons with greater ballistic, mobility, survivability, availability, and logistic performance to counter opposition threats and meet new doctrine and force requirements. These are translated into specific requirements for parameters such as range, rate of fire, emplacement and displacement time, system weight, stability, system and component reliabilities, external dimensions and environmental requirements, to name a few. The management of the resistive force opposing the travel of the recoiling mass on modern cannon artillery systems can minimize the weapon system reaction to firing. The minimizing of the reaction forces can result in reduced system weight, greater stability and lower weapon component loads. There are, however, limits to what can be done i.e., limits due to existence in the physical world and by interrelationships between the requirements themselves and their impact on recoil reactions.

In this paper, a review of the physical limits and realities that apply to the dissipation of recoil energy and an approach to configure a weapon systems recoil mechanism are presented. Only the gross weapon system inputs and reactions that affect or are affected by weapon recoil are addressed in this paper. The influence of recoil on weapon stability will be mentioned but will not be discussed in detail, due to equally strong influences by weapon system overall weight, its distribution, and weapon configuration that are not part of this paper.

2.0 Recent Trends In Weapon System Requirements

The user is always looking at increased system capability. This comes in many forms: ballistic performance, mobility, crew, and support requirements are just a few. These can directly affect aspects of the management of weapon recoil. How the recoil energy is dissipated in conjunction with system weight, configuration, and structure determines how the weapon responds to firing and its stability. Using US 155mm towed artillery as an example, the function and capabilities of the separate field gun and howitzer units has merged to a single system having the capabilities of both, Figure 1. Along with the merger of function, system weight has drastically decreased while weapon impulse has settled toward the upper end of the range. With the decrease in overall weight, both the non-recoiling and the recoiling masses are affected. While the merger of function and weight reduction complicates recoil management, the adoption of a single system to be supported significantly simplifies training and both support and logistics requirements.

The Designer's Dilemma – Recoil: What to do with it?



SYSTEM	TYPE	WEIGHT(kg)	WEAPON IMPULSE (N·Sec)	N·sec / kg
M1917	HOW	3750	30400	8.11
M1918M1	GUN	11300	49660	4.39
M1	GUN	12700	57630	4.54
M1/M114	HOW	5765	38170	6.62
M198	G/H	7163	46260	6.46
M777	G/H	4218	46260	10.97

Figure 1: US Army 155-mm Towed Artillery Systems

Ballistic performance has the most direct influence on system performance since it controls the firing input to the weapon. Greater range enables a weapon to cover a greater area without relocating, or greater standoff from the Forward Line of Own Troops (FLOT) for greater survivability. Rate of fire can provide greater weapon effectiveness requiring fewer systems for the same effect or the same effect in a shorter time period. The rate of fire places limits on weapon recoil cycle time affecting recoil length, velocity and weapon loads. Accuracy improvements of the weapon may allow fewer rounds for a given effect on target, which can affect the rate of fire and the associated restrictions.

Increased mobility of the weapon system, both in the tactical and the strategic sense, can have significant influences on recoil management. Tactical mobility characteristics, such as reduced weapon emplacement/displacement time, capability of helicopter lift, self-propelled capability, and cross-country performance, place strict requirements/limits on system size and weight. Strategic mobility characteristics, such as weapon system transport volume and weight, and the required logistics of both supplies and maintenance support personnel, also place requirements and limits, although less severe.

The user cost to own, utilize and support the weapon system also affects recoil management. Crew reductions can be realised by the addition of automation with its associated impact on system reliability or reliability allocations. The manpower required to service and support a weapon system is an expensive item and will quickly out pace the initial cost of the weapon. The annual cost for a crewmember has been estimated at over \$100,000. Reduction of operating expenses in these times of budget and manpower constraints has been a recurring requirement. Minimizing the logistics burden of a weapon system also has been a recurring requirement. Increased reliability and durability of the weapon, and the elimination or reduction of consumables, have been the primary thrusts.

The Designer's Dilemma – Recoil: What to do with it?

3.0 Physics of the situation and the available options

Since the invention of the cannon, the inventor and user have been stuck in the realm of Newtonian mechanics. Initially, cannon artillery consisted of trunnions installed directly to the barrel supported by a heavy carriage. Considerable weapon hop and rearward displacement occurred during firing. The weapon ground contacts will resist the firing reaction loads up to a point dependant upon the nature of the contacts (spades, grousers, stakes or floats) and the soil involved (rocky, loam, sandy or muddy types). Modern cannon artillery allows a recoiling mass to recoil against a resistive force over a relatively long stroke to counter the momentum exchanged during weapon firing. Weapon reactions are illustrated in Figure 2.

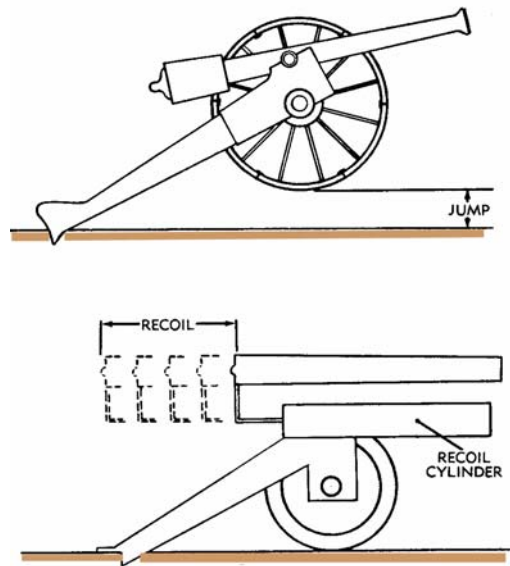


Figure 2: Weapon response with and without a recoil mechanism. From [1]

For weapon designers, the usable options to the configuration of modern recoil dissipating systems have been constrained by the principles, laws and limits of mechanical physics. The designers have been so constrained since these systems were first established and introduced over 100 years ago, being first employed late in the 19th century.

3.1 The Physics

Applied forces and their system reactions must be equal and opposite. The applied force resulting from firing the weapon must be balanced by the resulting weapon static and inertial reactions. This condition must hold for the system as a whole and between subassemblies and components within the system.

The change in momentum of a body acted on by an impulsive force is equal to the impulse. The area moment of the momentum (impulse) generated by the recoil mechanism to stop the recoiling mass and absorbed by system motion must balance the area moment of the driving momentum (impulse) applied to the weapon by the propellant gases and projectile. It must be equal in magnitude and opposite in direction. From the law of conservation of energy, energy can be dissipated or converted to other forms but it cannot be destroyed. The energy added to a system must be accounted for in its entirety.

3.2 Available Options

The original concepts for recoil dissipating mechanisms were derived for and applied to the then current weapons with trunnions fixed directly to the barrel. There are relatively few basic types of recoil mechanism that are practical under military requirements limitations. Two were identified and developed at the end of the 19th century. All throttle a working fluid and store part of the recoil energy to return the weapon to initial in-battery condition. The primary differences are the dependence or independence of the recoil mechanism components and the method of energy storage in the recuperator segment/mechanism. Originally, many configurations or refinements were not workable when patented. Only after other material/technology advances were made did they become practical.

The first type of recoil mechanism developed is the Fire-In-Battery (FIB) concept. The weapon is fired with the cannon at rest. This initial configuration is referred to as the in-battery condition. The cannon, along with all other recoiling components translate rearward to the end of travel before returning to the initial position. FIB recoil mechanisms that can be grouped into two classes depending upon the energy storage element in the recuperator system. The two classes are the hydro-spring and hydro-pneumatic systems.

The hydro-spring recoil mechanism was first patented in Austro-Hungary in 1890, spreading universally by the early 1900's [2]. The primary recoil braking force is generated by throttling a working fluid. A recuperator system or function, based on a mechanical spring for energy storage, is also provided. The compression of the mechanical spring provides a secondary recoil braking force and the force to return the recoiling mass to its original position.

The hydro-pneumatic recoil mechanism was first patented in France in 1894, also spreading universally by the early 1900's [2]. Again, throttling a working fluid generates the primary recoil braking force. A recuperator system or function, based on the compression of a gas spring for energy storage, is included. As with the hydro-spring mounting, the compression of the gas spring provides a secondary recoil braking force and the force to return the recoiling mass to its original position.

The second type of recoil mechanism is the Fire-Out-of-Battery (FOOB) or Differential concept, which was patented in France in 1907. The principle of the FOOB mounting is the reduction of the total weapon impulse applied to the weapon by initially generating a forward momentum to the recoiling mass, prior to weapon firing. Allowing the recuperator system to drive the recoiling mass forward to a specific point or forward velocity generates this forward momentum. Upon reaching this point or velocity, the process of firing the weapon is initiated. A few systems of this type have been developed, such as the original French 65-mm mountain gun, a German 55-mm anti-aircraft gun during World War II, and the M204 105-mm towed howitzer in the mid 1970's [3]. None were very successful.

4.0 Resulting System Trade-Offs

4.1 Single Recoil Systems

The most obvious approach to minimize the recoil reaction is to displace it over a greater distance and time interval using a FIB single recoil system. The lower the recoil reactions, the greater the weapon stability and/or the lighter the non-recoiling and/or structures can be.

The transmitted load to the non-recoiling parts by the gun mounting, when the weapon is fired, is approximated as a constant load using the relation [4]:

The Designer's Dilemma – Recoil: What to do with it?

$$K = [E_R / L] + W_R * \sin (QE) \text{ or } [(I_w^2 * g) / (2 * W_R * L)] + W_R * \sin (QE) \quad (1)$$

Where:

- K = Average (constant value) recoil load
- E_R = Recoil energy
- L = Recoiling mass total displacement
- W_R = Weight of recoiling parts
- QE = Weapon angle of elevation above horizontal

The recoil energy is estimated by:

$$E_R = [M_R * V_R^2] / 2 \quad (2)$$

Where:

- M_R = Mass of the recoiling parts
- V_R = Recoiling mass free recoil velocity

The Recoiling mass free recoil velocity is calculated by:

$$V_R = I_W / M_R \quad (3)$$

Where:

- I_W = Total weapon impulse = ($I_m + I_g$)
- I_m = Weapon impulse during in-bore period
- I_g = Weapon impulse during gas ejection period

For a given weapon impulse and recoiling mass, the weapon load is inversely proportional to the recoiling mass and the distance it is allowed to translate. Minimizing the force transmitted to the non-recoiling parts requires maximizing the recoiling mass and travel distance.

The Designer's Dilemma – Recoil: What to do with it?

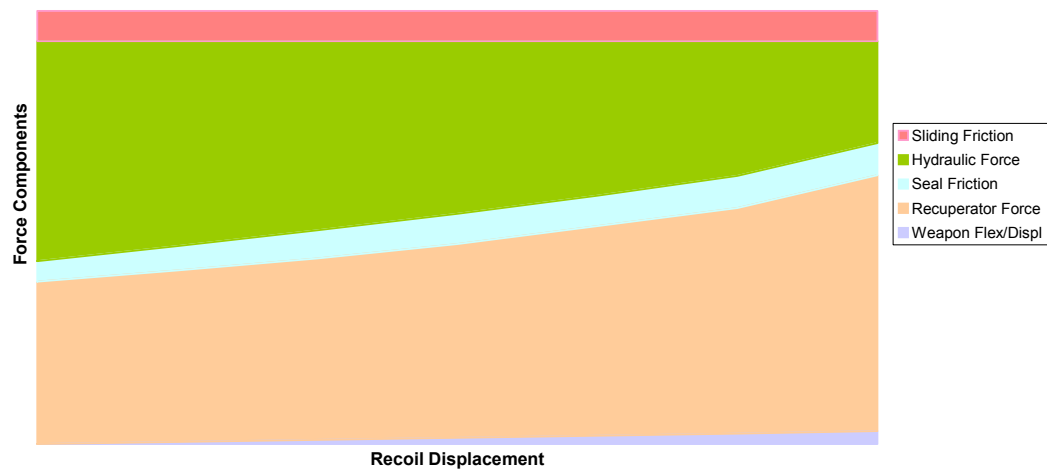


Figure 3: Typical Composition of Constant Recoil Load K or R

Since $W_R \cdot \sin(QE)$ is independent of total weapon impulse and total recoil distance and that the component is a small percentage of E_R / L for artillery systems, $W_R \cdot \sin(QE)$ will be ignored to evaluate the influence of total recoil distance on average recoil load. For illustrative purposes, the M198 155mm towed howitzer, is used. The total weapon impulse is 46260 N-sec and recoiling mass of 3252 kg. The resultant function, $K = [E_R / L]$, is plotted and shown in Figure 4.

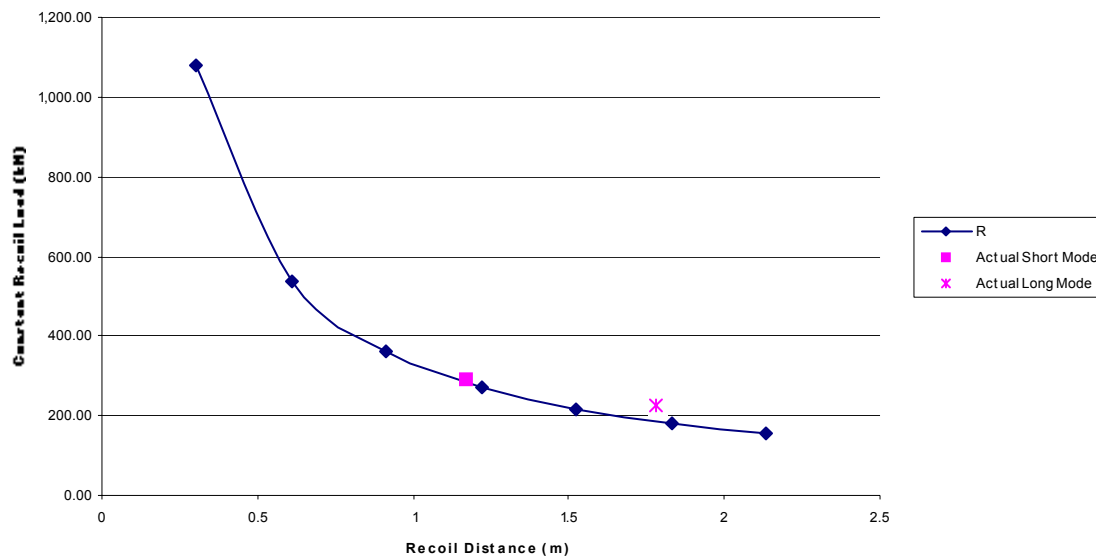


Figure 4: Theoretical average (constant) recoil load vs. recoil distance

The Designer's Dilemma – Recoil: What to do with it?

The peak recoil loads for the actual weapon system are shown for reference and are on the order of 3 to 23% higher than the constant value approximation depending upon recoil mode.

With the continual drive to minimize system weight, an obvious target is the recoiling mass with the cannon assembly in particular. Taking the partial derivative of recoil load to recoiling mass one gets:

$$\partial K / \partial W_R = [- (1 / W_R^2) * (I_w^2 * g) / (2 * L)] + \text{SIN} (QE) \quad (4)$$

This relation gives the approximated change in the average recoil load for a change in the recoiling mass. Since the product is negative, if one decreases the recoiling mass the average recoil load increases.

Another approach to a single recoil system is the FOOB system. The transmitted load to the non-recoiling parts by the gun mounting when the weapon is fired is again approximated as a constant load using the relation [4]:

$$K = [E_R / 4 * L] + W_R * \text{SIN} (QE) \text{ or } [(I_w^2 * g) / (8 * W_R * L)] + W_R * \text{SIN} (QE) \quad (5)$$

Again taking the partial derivative of recoiling load to recoiling mass one gets:

$$\partial K / \partial W_R = [- (1 / W_R^2) * (I_w^2 * g) / (8 * L)] + \text{SIN} (QE) \quad (6)$$

Comparing the FOOB relationships, eq. 5 and eq. 6, with the FIB relationships, eq. 1 and eq. 4, with all variables equal the value of the FOOB load is a quarter of the FIB value. However, to utilize the gain in reduced load of the FOOB system, inherent drawbacks must be accommodated, i.e. ignition delay variability varies the location/velocity of the recoiling mass when the main propelling charge ignites and recoil begins relative to the throttling control orifices. This causes erratic pressure spikes or dips in recoil brake performance. In weapon misfire/hang fire situations, the recoiling mass completes its run up to the forward end of the cradle rails and must be stopped resulting in a forward force on the weapon with the center of gravity well forward raising the stability risk of the weapon tipping over onto its muzzle. The system complexity tends to reduce reliability and increase maintainability issues of the weapon.

4.2 Dual Recoil System

An alternative to having a single recoil mechanism is the dual recoil system. This system was used on very heavy artillery systems from WWI into the 1950's. These systems consisted of railway guns and very heavy towed mobile guns and howitzers. An example is illustrated in Figure 5.

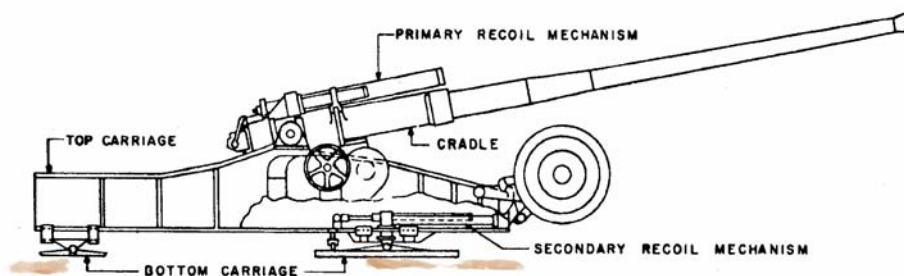


Figure 5: German 17-cm Kanone Mit Mrs. Laf. 18. From [4]

The Designer's Dilemma – Recoil: What to do with it?

The dual recoil system adds a secondary recoil mechanism between the top and bottom carriages. The modelled forces and masses of the system are shown in Figure 6.

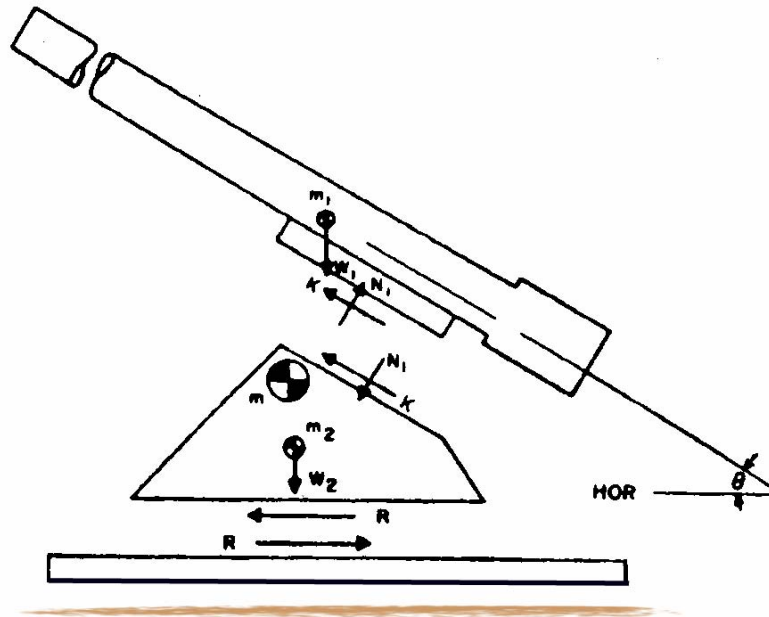


Figure 6: Free body diagram of dual recoil system. From [4]

This addition enables longer effective recoil distances in a limited space producing reduced recoil reaction force levels, extends the total time of recoil, and lower ground reactions. The dual recoil weapon has a reduced silhouette, greater stability and shorter guides than a comparable single recoil weapon. As with the single recoil system discussed above, the average (constant value) recoil load for the primary (K) and the secondary (R) can be approximated by [4]:

$$K = [E_{IR} / L_1] * \{1 - (L_2 * \cos^2(QE) / [L_1 * \cos(QE) + L_2 * ((M_{R1} + M_{R2}) / M_{R1}))]\} + W_{R1} * \sin(QE) \quad (7)$$

$$R = [0.5 * M_{R1} * \{V_R * \cos(QE)\}^2] / [L_1 * \cos(QE) + L_2 * \{(M_{R1} + M_{R2}) / M_{R1}\}] \quad (8)$$

Where:

L_1 = Primary recoil distance

L_2 = Secondary recoil distance

E_{R1} = Recoil energy input into primary recoil mass

M_{R1} = Primary recoil mass

M_{R2} = Secondary recoil mass

The Designer's Dilemma – Recoil: What to do with it?

As an example, a conceptual dual recoil version of the M198 155-mm towed howitzer is used to show the gain in reduced loads over the single recoil system. A mass of 182 kg was added to the mass of the top carriage to account for the secondary recoil system and rails. Assuming a secondary recoil distance of one meter and a weapon quadrant elevation of 0 mils, the resulting theoretical loads are shown in Figure 7.

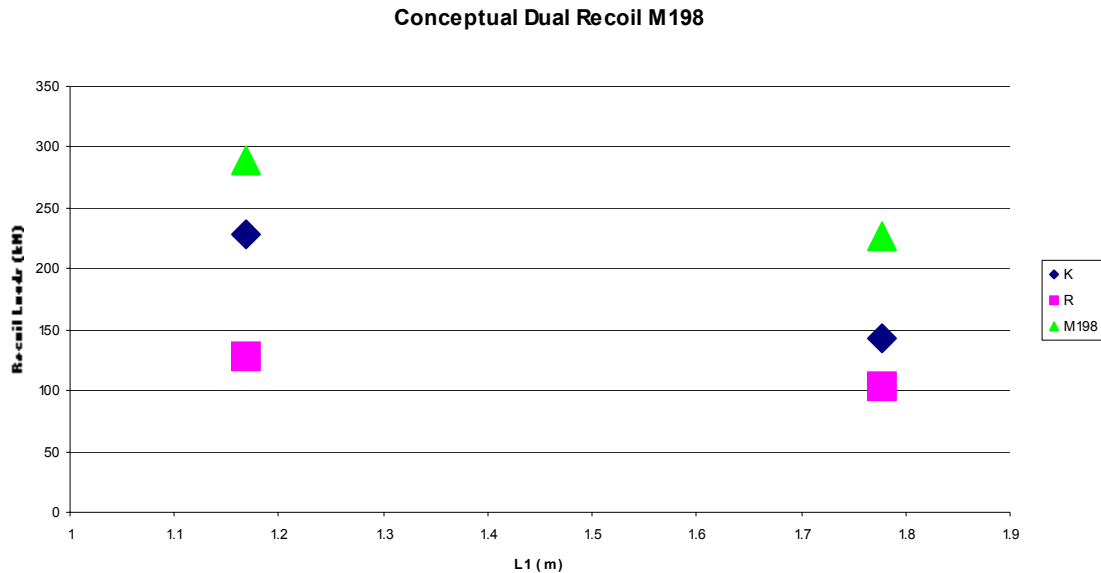


Figure 7: Primary (K) and secondary (R) recoil loads of conceptual dual recoil M198 155-mm towed howitzer. Actual single recoil mode loads for comparison

The lower carriage load of the dual recoil modification (R) is less than half the single recoil M198 howitzer. The primary recoil load of the dual recoil modification (K) is 21-37% lower than the single recoil M198 howitzer. There are consequences that must be accommodated when using a dual recoil system. Recoil cycle time is increased reducing rate of fire. System complexity is increased decreasing reliability and increasing maintenance. Also, the swept volume of the recoiling parts is increased.

4.3 Swept Volume

The volume created by the recoiling mass from the initial to full recoiled position translated through the range of allowed weapon quadrants of elevation from minimum to maximum is referred to as the recoiling mass swept volume. This volume must be kept clear, either fully or in part, of the firing cycle. As the recoiling mass recoil distance is increased, this volume is increased proportionally. This volume, particularly in self-propelled systems, can directly affect system size and weight through the internal volume.

4.4 Breech/Trunnion Relationship

The allowable recoil distance influences the location of the trunnion axis and the recoiling mass initial location relative to the trunnion axis. There are limits to recoil distance and trunnion location. The case of towed artillery is less restrictive as shown in Figure 8. The trunnion location must allow the recoiling parts to clear the upper and lower carriage. The recoil distance below the trunnion axis at maximum elevation must allow all breech components to remain above the soil surface.

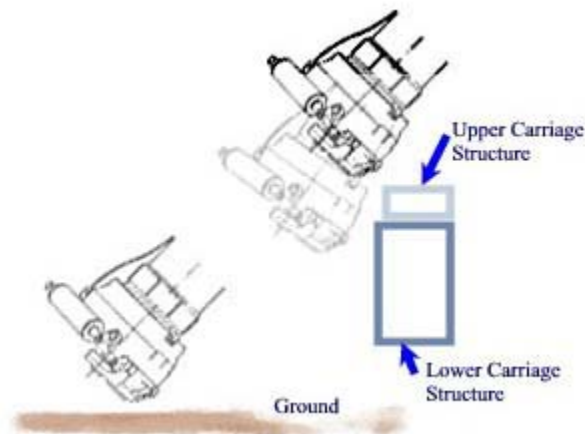


Figure 8: Towed system limiting recoil obstructions

In the case of self-propelled artillery, there are added restrictions as shown in Figure 9. As with the towed artillery case, the trunnion location must allow the recoiling parts to clear the upper carriage (cab) and lower carriage (hull), in particular, the front and rear segments of the cab bearing and the cab or hull rear compartment floor.

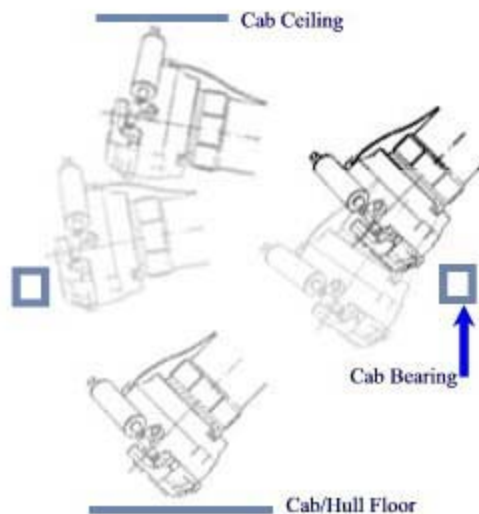


Figure 9: Self-propelled system limiting recoil obstructions

The relative location of the breech and trunnions can influence system characteristics. For example, using the configuration of the M198 155-mm towed howitzer (Figure 10) as a baseline, we have what can be considered a conventional configuration and variable recoil length.

The Designer's Dilemma – Recoil: What to do with it?

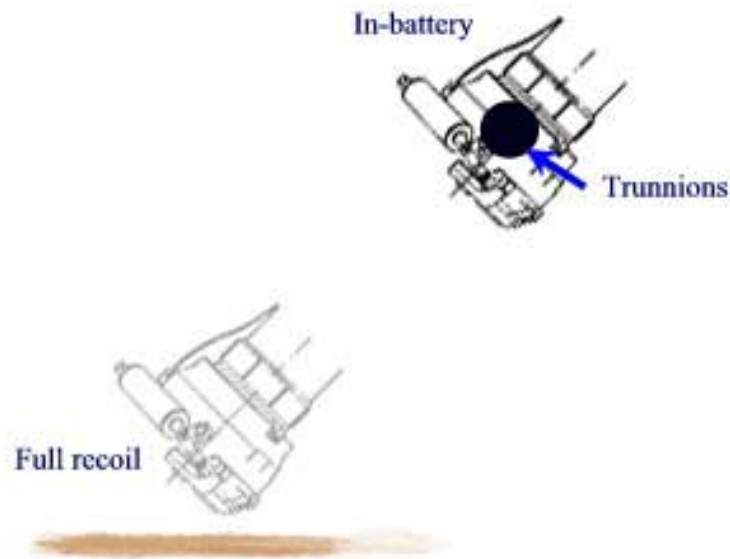


Figure 10: M198 155-mm towed howitzer trunnion location

Conversely the new M777 155-mm towed howitzer uses a breech location well forward of the trunnions enabling increased recoil length and reduced trunnion load that allows for a reduced recoiling mass and system weight while maintaining weapon stability (see Figure 11). This change did complicate weapon-loading procedures affecting rate of fire.

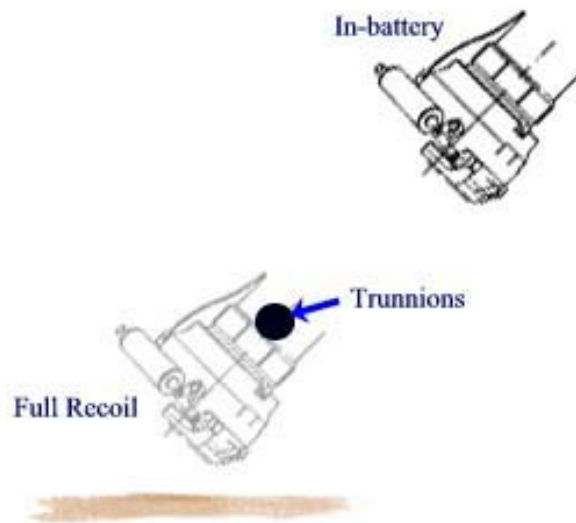


Figure 11: M777 155-mm towed howitzer trunnion location

4.5 Configuration vs. Reliability

By adding a function to vary the throttling of the working fluid as the weapon quadrant elevation varies, a compromise to the recoil distance restriction can be obtained, i.e. having a longer recoil distance at low quadrants of elevation where fewer limits exist and a reduced recoil length at high quadrants of elevation, minimizing the trunnion height. The addition of this function comes with a cost of added weight and complexity. The complexity of the recoil mechanism can adversely affect the weapon reliability, maintainability and availability. As a system becomes more complex, a longer chain of components, with individual failure rates, must function for successful operation. This arrangement is shown below in Figure 12:

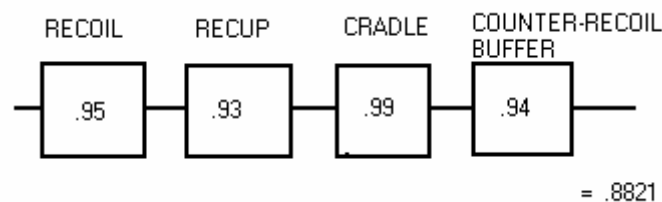


Figure 12: Reliability model – serial gun mount

In a series configuration, there is only one component for each functional part of the system thereby having the minimizing system weight. But with the requirement that all components must function for the system to be functional, the system reliability and availability is less than the individual components and may fall short of the allocation to meet the overall weapon system requirement. There are practical limits to the individual component reliabilities due to their physical natures.

Increased complexity in the form of redundancy may be required to meet weapon system reliability or availability requirements. The addition of identical components connected in parallel to one another allows functioning of the system even when one component fails, possibly at a reduced level. The reliability of that function is greater than that of the individual component reliability. This arrangement is shown below in Figure 13:

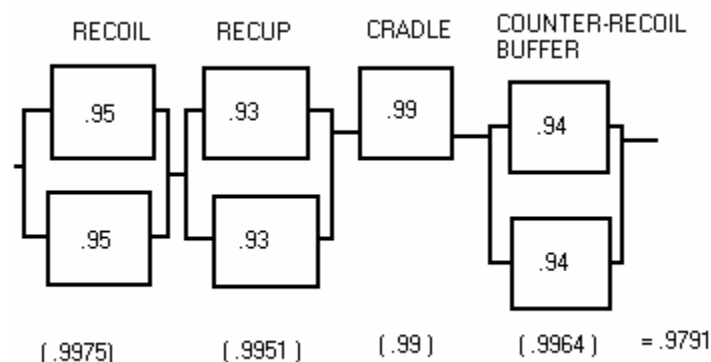


Figure 13: Reliability model – redundant gun mount

The Designer's Dilemma – Recoil: What to do with it?

The duplication of components to raise the system reliability also raises the weight of the system.

The increase in system complexity by the addition of additional functions, such as recoil brake function variability, adds factors to the serial chain further reducing the system reliability.

4.6 Muzzle Brakes

An obvious way to reduce firing loads, without lengthening the recoil stroke or reducing range, is to reduce the energy input applied to the weapon system. This is achieved by the addition of a device to the muzzle of the cannon, commonly referred to as a muzzle brake. A muzzle brake deflects the flow of the propellant gases, as they are discharged from the bore, creating a forward load on the recoiling mass. Common configurations and a functional schematic are shown in Figure 14. The more the gases are deflected, the greater the forward applied force and its impulse. Also, the larger the area on which the gas flow contacts, the greater the forward force and impulse. As the gases are deflected more and the contact area is increased, the weight of the brake (recoiling mass) as metal is added to provide the increasingly curved and/or larger area. The blast over pressure around the weapon, behind the muzzle, also increases.

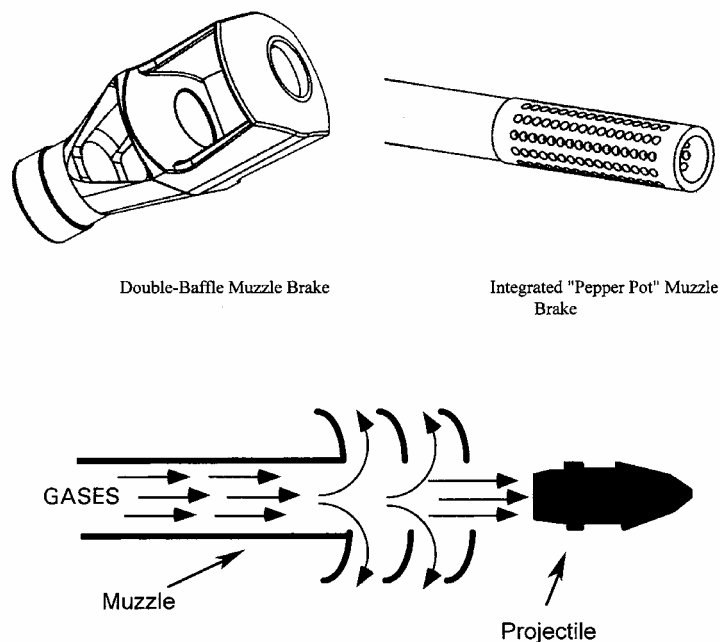


Figure 14: Muzzle brakes. From [5]

As an example, the breech force of a M198 155-mm towed howitzer fired with and without its medium efficiency muzzle brake is shown in Figure 15.

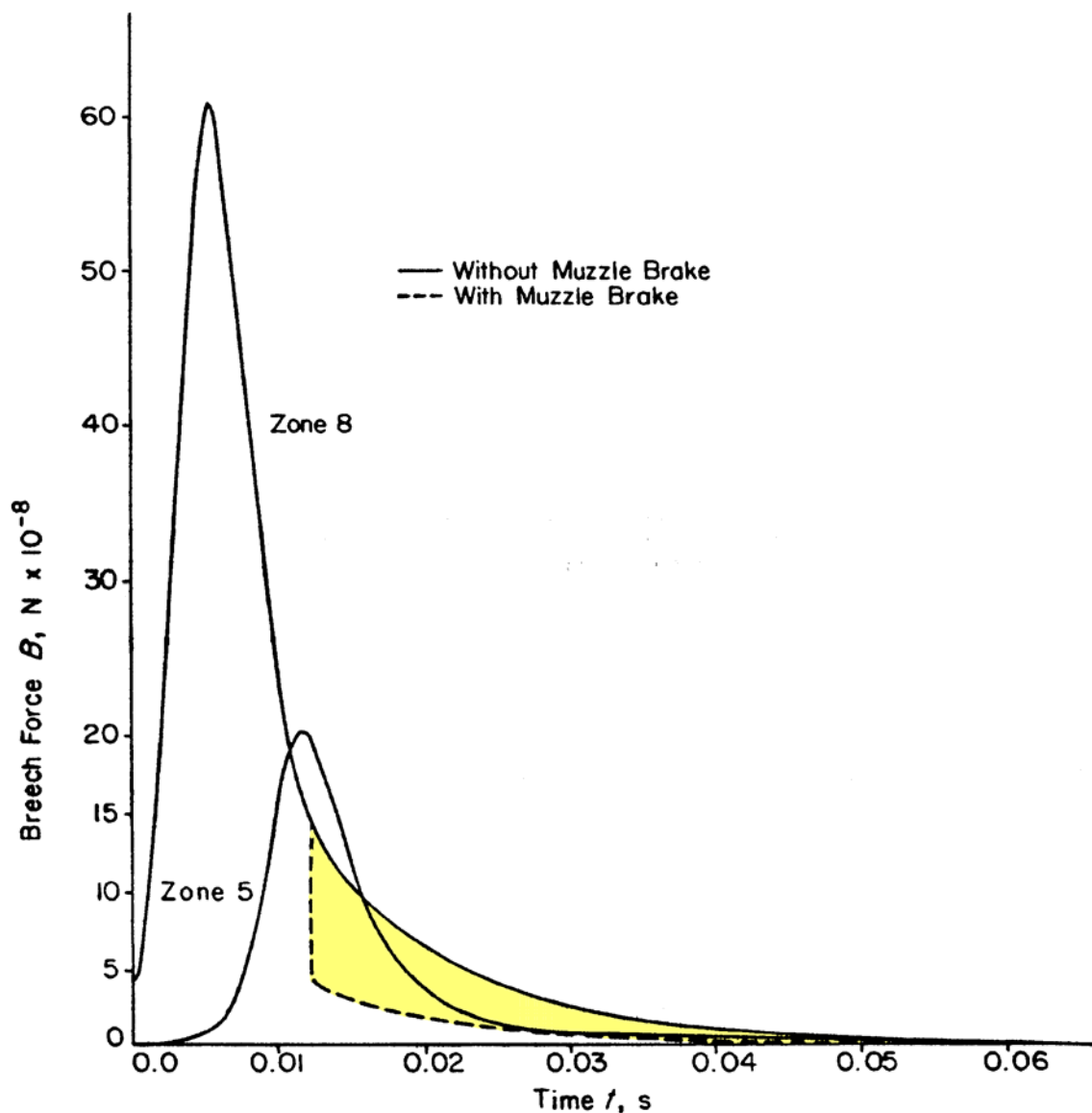


Figure 15: Impact on breech force by a muzzle brake. From [6]

A high efficiency muzzle brake, such as the muzzle brake used on the M109A6 155-mm self-propelled howitzer, will cause the breech force to go negative since the forward thrust generated by the brake exceeds the propellant gas pressure acting on the breech face.

The affect of adding a muzzle brake on the weapon's blast field is illustrated in the example of the M102 105-mm towed howitzer, with and without its medium efficiency muzzle brake. See Figure 16, below.

The Designer's Dilemma – Recoil: What to do with it?

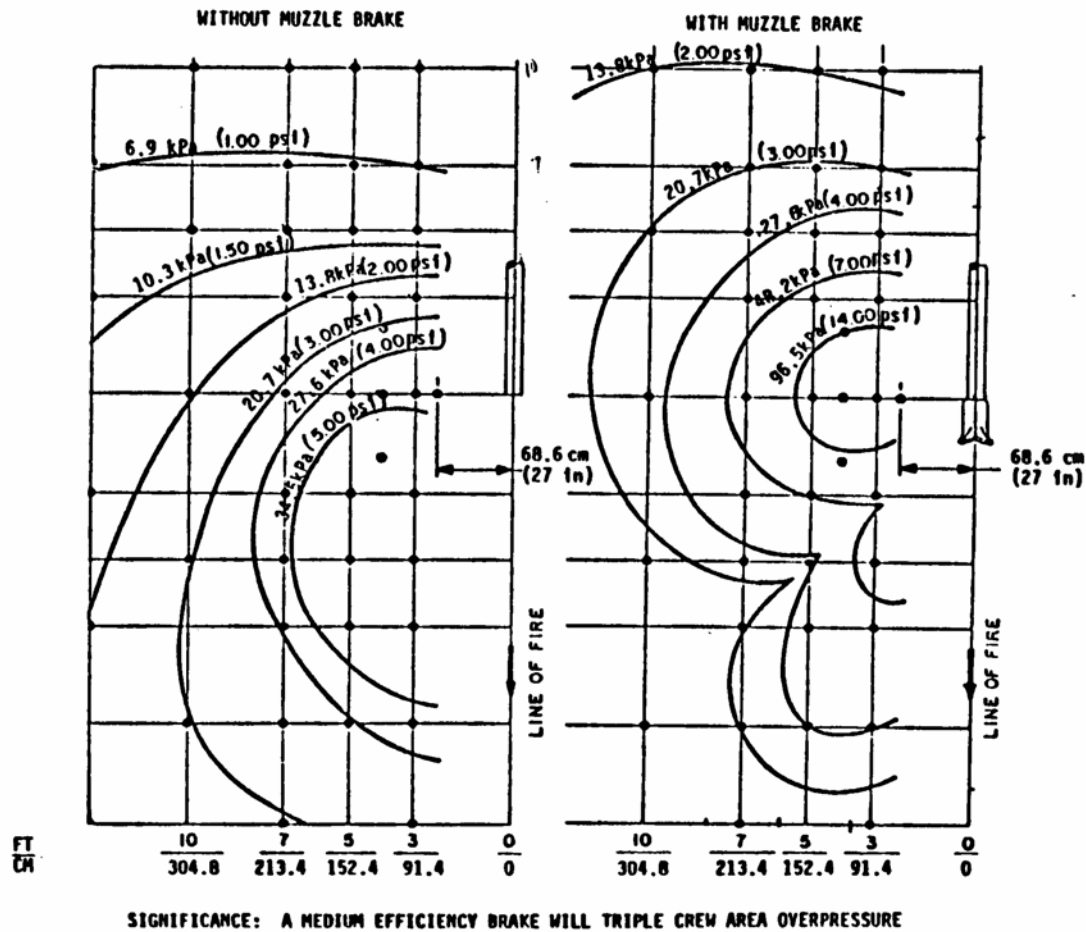


Figure 16: Impact on blast over pressure levels and distribution by a muzzle brake. From [7]

The blast flow field for a high efficiency muzzle brake can be seen in Figure 17 which shows a test firing of a high zone charge without flash suppression additives.



Figure 17: Gas flow deflection by a high efficiency muzzle brake

5.0 A possible way out?

Once the artillery designer is given a set of requirements for a new system, or an upgrade of an existing system, his journey begins. A process to follow could be:

- a) Review the user's requirements and goals
- b) Prioritize requirements, identifying Primary requirement(s) and Secondary requirements
- c) Develop a design to meet the primary requirement(s) and optimize secondary requirements
- d) Potential system performance/characteristics evaluation – Acceptable?
- e) Refine/rework/accept/reject the design or adjust the requirements until acceptable or cancelled

To help illustrate the process, the XM183 gun mount of the Advanced Armament System developed under the Division Support Weapons System (DSWS) and Howitzer Improvement Program (HIP) of the mid-1980s will be used as an example.

Review the user's requirements and goals to provide both a system overview and the basis for the evaluation of recoil management. List all requirements that affect weapon impulse and recoil mitigation that result from the set of user requirements. These may include requirements for range, projectiles to be fired and their zones, rate of fire, system weight, system dimensions, transportability, firing environments and availability/reliability/durability, and possibly others. For the XM183 gun mount program, they were:

Range: 40+ km with the M549A1 projectile and 24 km with the M483 projectile

Munitions: Compatible with all current projectiles and charges

The Designer's Dilemma – Recoil: What to do with it?

Gun Mount Reliability: 12,500 Mean Rounds Between Failure

Rate of Fire: 8 rounds per minute minimum

Minimize Logistic Requirement

Floor and ceiling locations, cab bearing location, capacity and space claim

Temperature Range: -45.6 °C to +62.8 °C

Prioritize and segregate the requirements into primary requirements that must be met and secondary requirements that are to be optimized but can be traded-off. The primary requirements identified were range, temperature range, the floor and ceiling locations, the cab bearing location, capacity and space claim. The primary requirements are equal in importance. The secondary requirements were rate of fire, gun mount reliability, and minimizing the logistics to support the gun mount with the rate of fire having the greatest importance, followed by reliability, and the logistic burden.

The design process was initiated to develop a configuration to meet all primary requirement(s) and optimize the secondary requirements. The specification of the hull floor and cab ceiling locations and the size, location and space claim of the cab bearing immediately established limits to the recoil distance for the system, effectively eliminating the first design goal of maximizing the recoil distance. The range requirements established the weapon impulse level. The dual range requirements for the M483 dual purpose improved conventional munition and for the M549A1 rocket assisted high explosive rounds directed the cannon design toward a ballistic scale-up of the then current 39 caliber M199 cannon. This resulted in the XM282 cannon having a chamber volume of 26.2 liters, a length of 58 calibers, and a new XM224 top charge. Together with the M549A1 projectile, a muzzle velocity of 1,115 m/s was achieved, producing a weapon impulse of 59,508 N-sec. The gun mount included a tube sleeve to which the cannon assembly attached to provide the sliding surfaces during recoil and to transmit the rifling torque to the cradle for simplified cannon design and increased fatigue life.

The second design goal was to maximize the muzzle brake efficiency to the extent the system and program constraints will allow. Existing muzzle brakes on the M109 family of self-propelled howitzers, and the M198 towed howitzer, had brake beta values of 1.45 and 0.7 respectively. Evaluation was restricted to these two since they were fully developed and fielded items requiring no development cost. These were both modelled to predict the resulting blast field with the XM224 charge. The XM282 cannon fitted with the high efficiency brake produced over pressure levels lower than the M185E1 cannon and the M203A1 charge due to the much greater standoff of the XM282's muzzle. The use of the high efficiency brake reduced the weapon impulse to 48,139 N-sec. With the limited recoil distance and high weapon impulse established, the average recoil load and recoiling mass was traded off, since the maximum load is set by the specification of the cab bearing. Adding the tube sleeve to interface between the cannon and the cradle added recoiling mass thereby lowering the recoil load. It also enabled removal of the torque key groove from the barrel, extending barrel life and simplifying barrel replacement.

The third design goal was to keep the gun mount simple. The requirement that the gun mount's reliability be 12,500 Mean Rounds Between Failure, just under twice the reliability of the then current M178 gun mount in the M109A2/A3 howitzers, drove the design away from this ideal. To meet this requirement, a simple series configuration was out of the question. A gun mount with dual redundant recoil brakes and recuperators and counter-recoil buffers with no moving parts was required along with a negotiated definition of what constituted a failure. The user and the developer agreed that a failure occurred when the system could not fire to a range of 11 km and a rate of 2 rounds per minute. This requirement was to be satisfied with only one

The Designer's Dilemma – Recoil: What to do with it?

recuperator and one recoil brake functional: the others modules either still connected, if down due to leakage failure, or disconnected but still in place, if down due to structural damage.

Although it was felt that the entire M109 self-propelled howitzer fleet did not need to have the extended range of the 58 caliber XM282 cannon, it was deemed highly desirable for it to be capable of being fitted (up-gunned), if needed. As a result, requirements for a rapid field change over from the long range XM282 cannon to a standard 39 caliber cannon, the XM283, or vice versa by a barrel change was added. With the gun mount designed for the larger and more capable XM282 cannon, the XM283 cannon could be fitted with the less efficient 0.7 muzzle brake with a resultant significant reduction in the blast over pressure field. The tube sleeve supports the breech during barrel change and also removes the torque transfer from the barrel.

To minimize the maintenance burden, a modular approach was applied. Both the recoil brake modules and the recuperator modules were removable by the crew or forward maintenance contact team and could be replaced within five minutes in the forward area. Rod wipers, new seal configurations, and integrated replenishment and maintenance plumbing and filtering were incorporated in the recoil brake modules. Barrel replacement could be accomplished in the field or forward area, without requiring withdrawal of the weapon to the rear. With the use of a wrecker or crane, the cannon barrel could be removed, after the removal of the breech ring/barrel key, and withdrawn out the front of the tube sleeve without requiring removal of the gun mount from the weapon or disruption of the fire control interfaces. The replacement or reinstalled barrel only required insertion into the tube sleeve, rotation to engage the interrupted threads, installation of the locking key, and bore sighting the barrel with the fire control.

The resulting gun mount configuration is shown below in an exploded layout of the individual modules and components, Figure 18.

Periodically during development, system performance/characteristics were evaluated to ascertain acceptability. By analysis and computer simulation, it was concluded that the design met all the requirements summarized below:

Range – met

Recoil cleared floor, ceiling and bearing restrictions - met

Single recoil mode design utilized - met

Total recoil retarding force through trunnions below the bearing limit load - met

Initial durability of components demonstrated by gymnastication - met

Recoil brake and recuperator module performance demonstrated by live fire test – met

Field change maintenance capabilities demonstrated. - Met

The Designer's Dilemma – Recoil: What to do with it?

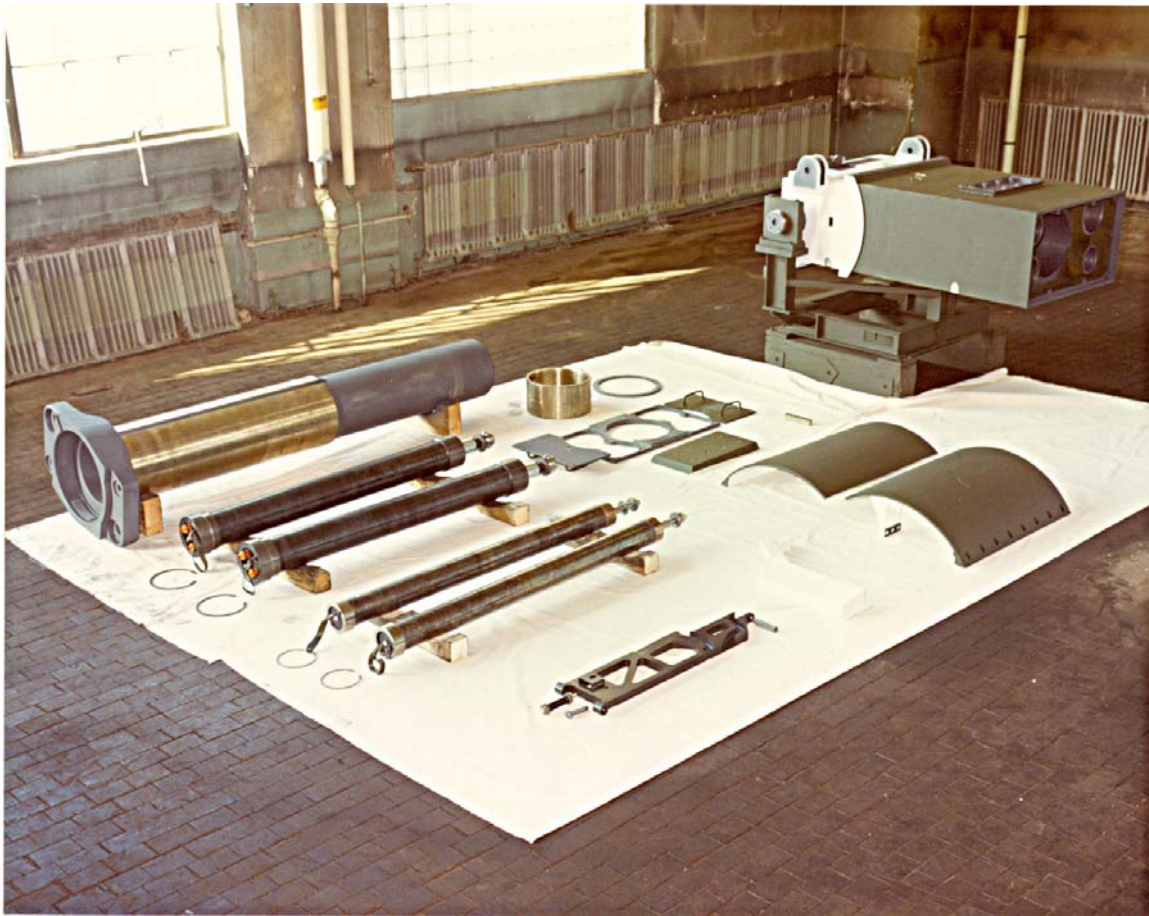


Figure 18: Components of the initial XM183 gun mount prototype SN0

Using the initial prototype, the design was evaluated under simulated weapon firing using a gymnasticator to evaluate performance and durability. All characteristics except counter recoil buffing performed as expected. Due to the simulated weapon functioning by the gymnasticator, the potential problem with counter-recoil buffing could not be identified as a design flaw or due to the way firing was simulated. The initial prototype was evaluated for its maintenance and logistics aspects. All components performed as expected. The cradle of the initial prototype was replaced with a cradle with less armour protection, designated SN1. During initial live firings, all characteristics except counter recoil buffing performed as expected. The testing verified a design failure in the counter-recoil buffing system.

The spear buffer approach for the counter-recoil buffing system could not be modified to meet required performance level. This required a change of the counter-recoil buffer configuration to dual independent dashpot buffers, with a resultant reduction in the theoretical Mean Round Between Failure (MRBF) performance. This would have required a reduced MRBF requirement. Due to lack of user support, the Advanced Armament program, of which the XM183 gun mount was a part, was cancelled. The decision that went forward was the upgrade of M109 self-propelled howitzer with a more robust cannon, the M284, to replace the M185 cannon in lieu of the Advanced Armament System resulting in version fielded as the M109A6 Paladin.

6.0 Conclusions

There is no such thing as a free lunch. Every benefit has a cost. The designer is limited in his basic approach to dissipate weapon momentum due to firing to: Fire-In-Battery or Fire-Out-Of-Battery, and either in single or dual recoil system configurations. In both cases, primarily a recoil retarding force applied over distance dissipates the weapon momentum. The most efficient muzzle brake allowable should be used to minimize the weapon momentum.

Provided the designer is given non-conflicting primary requirements and latitude in trade-off of secondary requirements, systems can be configured within a limit. There is a limit to the minimum system weight for a given input energy/momentum level. The configuration type and recoil system type will set recoiling mass and resulting recoil loads for the driving input. To support these loads, the required support structure to accommodate these loads will require a minimum weight due to material strength and deflection requirements. Added together, the recoiling and non-recoiling structural mass will set a minimum system weight.

References

- [1] Principles of Artillery Weapons, TM 9-3305-1, Department of the Army, November 1956 pg. 109
- [2] Recoil Mechanisms, Volume 11, Artillery Design Data, Ordnance Department, U.S. Army, June 1, 1949
- [3] Ian V. Hogg, The Illustrated Encyclopaedia of Artillery, Quarto Publishing plc, London, England, 1987
- [4] Recoil Systems, AMCP 706-342, US Army Materiel Command, September 1963
- [5] Mechanical Design, ME402 Class Text, United States Military Academy, West Point, New York, Fall 1998
- [6] Design of Towed Artillery Weapons System, MIL-HDBK-785 (AR), US Army Management Engineering College, 30 March 1990, pg. 2-12
- [7] Weapon Design, Course Notes, Armament Technology Seminar, Mark Salisbury, TACOM-ARDEC, Picatinny Arsenal, NJ

The Designer's Dilemma – Recoil: What to do with it?

