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TECHNICAL REPORT ARCCB-TR-02007

A FIRE OUT-OF-BATTERY TANK GUN: THEORY AND SIMULATION

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MAY 2002

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank)*

2. REPORT DATE
May 2002

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
A FIRE OUT-OF-BATTERY TANK GUN:
THEORY AND SIMULATION

5. FUNDING NUMBERS
AMCMS No. 6226.24.H180.0
PRON No. 4A1C1FYA1ABJ

6. AUTHORS
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-02007

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Presented at the 10th U.S. Army Gun Dynamics Symposium, Austin, TX, 23-26 April 2001.
Published in proceedings of the symposium.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

As part of the *Army After Next* effort, TACOM-ARDEC's Benet Laboratories undertook a radical departure from current tank gun recoil to engineer a soft recoil tank gun. Such a leap in technology may be required to enable a lightweight future combat system to withstand the recoil imparted by a large caliber gun, especially during fire on the move. Although soft recoil is not new to smaller caliber guns and howitzers, implementation for a large caliber tank gun is unprecedented. The theoretical foundations of this recoil management technology will be presented here. Experimental test results from a 105-mm fire out-of-battery tank gun demonstrator will be presented in a separate report.

14. SUBJECT TERMS
Gun Mount, Soft Recoil, Fire Out-of-Battery, Future Combat System

15. NUMBER OF PAGES
20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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ACKNOWLEDGEMENTS

The authors acknowledge the contributions to advanced recoil of

- Larry Burton, Army Research Laboratory.
- Stephen Floroff, Picatinny Arsenal.
- Kenneth Wynes, who recently retired from Rock Island Arsenal.

INTRODUCTION

The extreme lethality goals of the future combat system (FCS) program require innovative armament solutions to circumvent traditional engineering barriers. Fire out-of-battery (FOOB) recoil constitutes a recoil momentum management technology inspired by the need to meet the requirements of the Army's Objective Force.

One of the clearest operational requirements of any FCS vehicle is the need to be tactically transportable via a C130 class aircraft, such as the C130J. Although less clear in engineering specifications, the lethality requirements for FCS vehicles are substantial; in many respects, the lethality must be greater than that attained by the M1A2 series main battle tank. Engineering projections for future large caliber gun main armaments anticipate that launch momentum may be in the neighborhood of 35,000 N·s (approximately 8000 $lb_f \cdot s$). This magnitude is approximately 15% higher than incurred when firing the current state-of-the-art 120-mm M829A2 round from the M1A2. A concept image of such a vehicle is depicted in Figure 1. The image is intentionally vague to avoid skewing the community towards preferred configurations and inadvertently inhibiting novel approaches (ref 1).

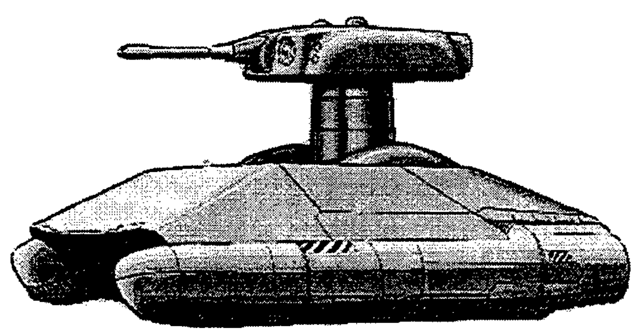

Figure 1. Artist's conception of a future combat system vehicle employing a large caliber gun main armament.

Integrating a main armament system, having recoil momentum greater than that developed by the current main battle tank, with a future vehicle, having a mass less than one-third that of the main battle tank, is an armament engineering challenge that will require unprecedented solutions. (For the case at hand, the FCS exceeds the Ogorkiewicz limit of 900 N s/tonne (ref 2) by a factor of two.) FOOB recoil (also commonly termed "soft recoil") is one proposed solution path.

HISTORICAL PRECEDENT

The first known application of FOOB recoil is attributable to the French Schneider-Ducrest canon de 65 de Montagne Modele 1906 (ref 3).

Table 1 presents a listing of modern US Army howitzer FOOB gun efforts as provided by noted ARDEC recoil engineer Stephen Floroff (ref 3). Much of the advancement in US FOOB recoil efforts over the past three decades may be attributed in part to Kenneth Wynes, of Rock Island Arsenal, IL.

TABLE 1. MODERN US HOWITZER FOOB EFFORTS

1957	Modified M101	Proof of concept towed howitzer employing FOOB.
1965	Test Fixture	Fabrication and test of first ground-up FOOB weapon.
1971-1978	M204	Development and type classification of FOOB howitzer (ref 4). Only six were made.
1975-1976	LCSR	Large caliber soft recoil gun effort. Revealed ignition delay challenges.
1995-1996	VIPER	Moderate use of FOOB to mitigate high zone recoil (ref 5).
1997-1999	ATLAS Test Bed I	Advancement of VIPER for the Advanced Technology Light Artillery System (ATLAS).

ANALYSIS

Basic Equations Governing Recoil

Newton's second law equates the acceleration of an inertial body to the force required to accelerate it, equation (1). Integration of Newton's second law in space for a free body determines the kinetic and imparted energy. Equation (2) results in the familiar result that the kinetic energy of an object may be computed as one half the mass of the object multiplied by the square of its velocity. Imparted energy may be computed as the integral of force over its applied length, as shown in equation (3), which by the equality of equation (1) is equivalent to equation (2). Integration of Newton's second law in time for a free body determines the momentum. Momentum may be computed as the integral of force over time, which is equivalent to the product of an object's mass and its change in velocity, equation (4).

$$\bar{F}(t) = m\bar{a}(t) \tag{1}$$

$$\Delta KE = KE(t_f) - KE(t_f) = \int_{\bar{x}(t_o)}^{\bar{x}(t_f)} m\bar{a}(t)\cdot d\bar{x} = \frac{1}{2}m\left[\bar{v}(t_f)\cdot\bar{v}(t_f) - \bar{v}(t_o)\cdot\bar{v}(t_o)\right] \tag{2}$$

$$\Delta E = E(t_f) - E(t_f) = \int_{\bar{x}(t_o)}^{\bar{x}(t_f)} \bar{F}\cdot d\bar{x} \tag{3}$$

$$\Delta\bar{I} = \bar{I}(t_f) - \bar{I}(t_o) = \int_{t_o}^{t_f} \bar{F}(t)dt = \int_{t_o}^{t_f} m\bar{a}(t)\,dt = m\left[\bar{v}(t_f) - \bar{v}(t_o)\right] = m\Delta\bar{v} \tag{4}$$

Where:

$\bar{a}$ is the acceleration of the object
E is the imparted energy
$\bar{F}$ is the applied force
KE is the kinetic energy of the object
$\bar{I}$ is the momentum imparted
m is the mass of the object (assumed constant)
t is time
t_o is the time at the commencement of the event
t_f is the time at completion of the event
$\bar{v}$ is the velocity of the object
$\bar{x}$ is the displacement of the object relative to an inertial reference frame
$\bar{\bullet}$ an over-bar denotes a vector quantity
Δ indicates the change between the commencement and completion of the event.

It is worthy of note that displacement, velocity, acceleration, force, and momentum are vector quantities. For a typical analysis of a gun, it is known that the recoil forces of interest—projectile motion, recoil motion, and momentum—all lay parallel to the centerline of the gun barrel. (The effect of bore centerline flexure and misalignment may be considered to have a negligible effect on recoil energy and momentum for the purpose of this discussion.) Therefore, the magnitudes of the vector quantities are often used in computations without reference to their actual form as vectors. This is a valid simplification and will be understood to be the case when the over-bar notation is not used in later equations. Erroneous concepts to dissipate or redirect momentum using forces internal to the system (FCS vehicle) may arise when this is not understood.

In the case of determining the muzzle energy of a launch mass, equation (3) is used with the ballistic force applied over the traverse of the gun. It is worth noting that a subtle assumption often made in computing the muzzle energy using equation (3) is that the launcher recoils so little during the launch, that the difference between the launch length relative to the recoiling gun and that of an earth inertial reference frame is negligible. In fact, the recoiling gun will pull away from the projectile during launch, decreasing the effective launch length by a percentage that may be closely approximated by dividing the sum of the projectile mass and half the propellant mass by the mass that recoils with the cannon, when no significant external forces are applied to the gun. (This will later be derived in equation (10).)

This motion of the recoiling cannon manifests as its kinetic energy of recoil. The recoil energy is imparted to the gun by the rearward expansion of the propellant gases as the chamber recoils rearward; thus, the kinetic energy of recoil is extracted from the internal energy of the propellant gases, effecting a modest reduction in their pressure. The resulting degradation in muzzle velocity is discernible; however, from a parametric design perspective, it has little effect on ballistic performance for realistic gun systems. For example, simple NOVA (ref 6) analysis of the M256/M829A2 indicates that doubling the recoiling mass of the gun (from about 1800 kg) will increase the muzzle velocity by just less than one quarter of one percent and thus increase the muzzle energy by nearly a half a percent. Management of this recoil momentum and energy, and their effect on the fighting vehicle, is critical to the success of any future combat system.

Fire Out Of Battery

Fire out of battery is a technique to dramatically reduce the trunnion loads of recoil by pre-accelerating the recoiling cannon mass forward—prior to firing. Taken to its logical extreme, half of the launch momentum may be imparted prior to firing. Using equations (4) and (2), we may determine that the recoil system must provide one-fourth of the traditional recoil kinetic energy up-front. Upon firing, the momentum imparted to the cannon will reverse its velocity. The first half of the launch momentum will bring the pre-accelerated cannon to rest while the second half will impart rearward momentum of equal magnitude and kinetic energy to that endowed during pre-acceleration. A recoil system that dissipates no energy may thus extract the kinetic energy of recoil from the latter half of a previous firing and store it to pre-accelerate the next firing. A low friction recoil system utilizing highly pre-loaded and soft springs would work exceedingly well in this application.

The advantage of FOOB is that the recoil stroke or trunnion load, or both, may be dramatically reduced. By holding one constant, the other may be reduced by a factor of four. Disadvantages of FOOB include misfire and hang-fire handling, and degradation in accuracy.

Some Simple Relationships

Although it is true that the recoil motion and energy imparted to a cannon during firing will reduce the muzzle velocity somewhat, the effect tends to be very small, less than a percent. Therefore, the launch momentum imparted to a recoiling gun by a given bullet will also tend to remain nearly constant regardless of the recoil motion of the gun.

Assuming the recoil momentum imparted by a given round to be independent of recoil motion will allow for a simplified discussion of the governing relationships between the system parameters.

An additional simplification in the present study is to assume that the recoil momentum imparted to the gun results in a discrete change in the recoil velocity of the recoiling cannon. This may be considered a free-recoil assumption while the ballistic forces are applying the momentum to the gun. (If the change in velocity were instantaneous, this would be the Dirac delta function, $\delta(t)$, approximation.) Because of accuracy concerns, current tank gun design philosophy is to approach free recoil in practice by delaying the application of recoil forces until the bullet has left the gun (ref 7), or at least until bending waves caused by any asymmetries in the recoil loading cannot reach the muzzle prior to shot-exit (ref 8). Because the majority of the launch momentum is imparted prior to shot-exit, it may be seen that the free-recoil assumption is approached in practice. This assumption becomes compromised as the energy imparted to or extracted from the recoiling gun during the ballistic event by external loads (such as recoil cylinders) begins to become comparable to the energy imparted or extracted by the ballistic event itself. As the ballistic loads tend to be at least an order of magnitude greater than the recoil cylinder loads, the free-recoil assumption remains quite viable even for gun systems that do not allow for free recoil. FOOB guns for example do not allow for free recoil. For the simulation to be presented later in Figure 5b, this has a 2% effect on the change in recoil velocity during firing.

Computing Recoil Velocity and Energy

Using the above two assumptions, we can compute the change in recoil velocity (from the commencement of ignition of the round to the completion of blow-down) using equation (4) as shown below in equation (5). For a gun initially at rest (fire in battery [FIB]), this may then be related to the kinetic energy of recoil using equation (2) as shown in equation (6).

$$\Delta\bar{v}_r = \bar{I}_L / m_r \tag{5}$$

$$\bar{v}_r(t_o) = 0 \Rightarrow \Delta KE_r = \frac{1}{2} m_r \left|\Delta\bar{v}_r\right|^2 = \frac{1}{2} m_r \left|\bar{I}_L / m_r\right|^2 = \frac{1}{2m_r}\left|\bar{I}_L\right|^2 \tag{6}$$

Where: I_L is the launch momentum imparted (often termed the impulse of the round) including any muzzle brake effects

m_r is the recoiling mass (gun barrel, breech, etc.)

$\bar{v}_r$ is the velocity of the recoiling mass

ΔKE_r is the kinetic energy of recoil.

As equation (6) makes clear, the kinetic energy of recoil is inversely proportional to the recoiling mass, and it increases to the square of launch momentum. Thus, efforts to produce lightweight cannons inevitably result in recoil challenges. Similarly, seemingly modest increases in recoil momentum result in substantial increases in the kinetic energy of recoil. (The loss of thermal mass for burst fire is another significant issue for lighter weight barrels.)

The momentum transferred to the recoiling cannon during the launch of a projectile is subsequently imparted to the platform to which the gun is mounted. Recoil systems allow the recoiling cannon to move within the gun mount, and apply braking loads to bring it to rest over a period of time that is longer than the ballistic event. Typically, the time for the cannon to be brought to rest is an order of magnitude longer than the in-bore time of the bullet. Thus, the recoil loads may be much lower than the ballistic loads while still satisfying the conservation of momentum.

Of principal concern to the armament engineer is the recoil stroke length that must be dedicated to allow the cannon to be brought to rest using reasonable recoil forces. This trade-off between the magnitude of recoil forces and the extent of recoil stroke is determined by the magnitude of the kinetic energy that must be extracted by the applied recoil load. The extracted energy, equation (3), must be equal to the kinetic energy of recoil, equations (2) and (6), by the equality of Newton's second law, equation (1). Using current variable orifice hydraulic brake technology allows us to tailor the recoil system for a given gun to provide a nearly flat force versus stroke profile—for the highest momentum (worst case) round fired. (For modern tank guns, the force is intentionally kept low for a very brief time for accuracy considerations, as mentioned earlier.) For rounds of lesser momentum, the maximum loads are always lower than for the worst case; however, they tend to fall off in force as the gun traverses its recoil stroke. Therefore, a simplifying assumption that may be approached in design practice is to assume free recoil of the gun until shot-exit, followed by a step function recoil force until the recoiling gun is brought to rest—for the highest impulse round to be fired. The accuracy of this assumption is not high, but is perhaps a good estimate to within 10 to 20%. Under this assumption, the integration of equation (3) degrades to integration over a rectangular region. Thus, the product of the recoil force and the stroke over which this force is applied must be equal to the kinetic energy of recoil.

Computing In-Bore Free-Recoil Stroke

The free-recoil stroke of the gun up to shot-exit may be computed by noting that the action of internal forces alone cannot change the center of mass of a system. Thus, the motion of the recoiling barrel may be related to the motion of the mass of the projectile and the propellant gases, up to shot-exit, using an inertial reference frame in which the initial recoil velocity immediately prior to ignition is zero. (For a stationary FIB gun, an earth inertial reference frame would suffice.) These motions may be tracked using a selection of variables as depicted in Figure 2.

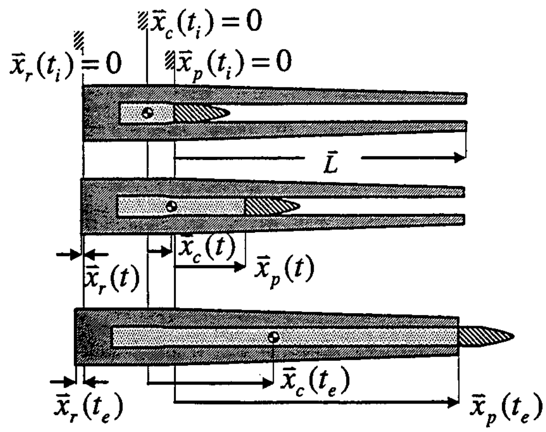

Figure 2. Depiction of a gun, projectile, and propellant system with center of mass of propellant indicated.

$$\bar{x}_r(t)m_r + \bar{x}_c(t)m_c + \bar{x}_p(t)m_p = 0 \quad \forall t : t_i \le t \le t_e \tag{7}$$

$$\bar{x}_r(t_e) = -\bar{x}_c(t_e)m_c/m_r - \bar{x}_p(t_e)m_p/m_r \tag{8}$$

$$\bar{L} = \bar{x}_p(t_e) - \bar{x}_r(t_e) \tag{9}$$

Where: $\bar{x}_r(t_i) = \bar{x}_c(t_i) = \bar{x}_p(t_i) = 0$ by suitable definition as shown in Figure 2
$\bar{L}$ is the launch stroke of the gun barrel
m_c is the propellant (charge) mass
m_p is the projectile mass
t_e is the time at shot-exit
t_i is the time at commencement of ignition
$\bar{x}_c$ is the position of the center of the propellant (charge) mass
$\bar{x}_p$ is the position of the base of the projectile
$\bar{x}_r$ is the recoil position of the cannon.

Perspective on the in-bore free-recoil stroke may be gained by recognizing that the free-recoil displacement of realistic guns is very small relative to the launch stroke. Further, the center of mass of the propellant tends to follow the projectile with about one half the displacement. Thus, at shot-exit the propellant mass has moved about half of the launch stroke. (This approximation neglects the length of the chamber, chambrage ratio, and any density gradient in the propellant gas column.) Thus, the free-recoil stroke may be estimated using the above assumptions and equation (8) as:

$$\bar{x}_r(t_e) \approx -\frac{L}{m_r}\left(m_p + m_c/2\right) \tag{10}$$

For the 105-mm M35/M900 the charge mass, projectile mass, launch length, and recoiling mass are approximately 6 kg, 6 kg, 4¾ m, and 1090 kg, respectively. Using equation (10) allows us to estimate a distance of –39 mm (–1½ inches).

Although blow-down will continue to impart momentum to the gun after shot-exit, and muzzle brake activity occurs in its entirety after shot-exit, it is a reasonable approximation to endow the recoiling gun with the blow-down momentum as a Dirac delta function at shot-exit. (Thus, the time at shot-exit will be considered the completion of the event in equation (6).) Using this assumption gives:

$$\bar{v}_r(t_i) = 0 \Rightarrow \bar{v}_r(t_e) = \bar{I}_L / m_r \tag{11}$$

$$\bar{v}_r(t_i) = 0 \Rightarrow KE_r(t_e) = \frac{1}{2} m_r \left|\Delta \bar{v}_r(t_e)\right|^2 = \frac{1}{2 m_r} \left|\bar{I}_L\right|^2 \tag{12}$$

Computing Recoil Force

Using a recoil system idealized for a flat force profile to bring the gun to rest (i.e., the completion of the recoil event) will require setting the product of the additional recoil stroke and the recoil force to be equal to the magnitude of the kinetic energy of recoil at shot-exit.

$$\left|\left(\bar{x}_r(t_o) - \bar{x}_r(t_e)\right) \cdot \bar{F}_r\right| = KE_r(t_e) = \frac{1}{2\, m_r} \left|\bar{I}_L\right|^2 \tag{13}$$

If the Dirac delta function approximation to the entire launch momentum is employed and no provision is included for free recoil, the ignition commencement and shot-exit times become coincident and the net recoil stroke estimate under these approximations becomes:

$$\left|\Delta \bar{x}_r \cdot \bar{F}_r\right| = \frac{1}{2\, m_r} \left|\bar{I}_L\right|^2 \tag{14}$$

As FOOB guns inherently do not provide for free recoil, equation (14) should be used when comparing FOOB to FIB recoil. To do otherwise would lend an unfair advantage to FOOB.

It is worth noting that, because the recoil stroke is negative (backwards recoil) and the force is forwards (decelerating the reward recoiling gun), the recoil cylinders may be considered to extract the kinetic energy of recoil from the gun. Traditionally, this energy is ultimately dissipated as heat from the recoil cylinders.

Computing FOOB Recoil Force

In the case of FOOB, half of the momentum may be imparted prior to firing. This is achieved by accelerating the gun forward from the rearward extent of recoil to half the free-recoil speed computed in equation (11). Upon firing, the first half of the launch momentum brings the pre-accelerated cannon to rest while the second half endows it with the second half of the launch momentum, reversing the velocity of the pre-accelerated cannon to half the free-recoil velocity, equation (11). This all takes place very quickly during the interior ballistics, and thus may be approximated as a Dirac delta function, except for the forward intrusion of the cannon during firing.

Using FOOB allows the same recoil stroke to be traversed twice, once forward and once rearward. Considering either stroke independently of the other:

$$\left|\Delta\bar{x}_r \cdot \bar{F}_r\right| = \frac{1}{2\,m_r}\left|\frac{\bar{I}_L}{2}\right|^2 = \left(\frac{1}{4}\right)\frac{1}{2\,m_r}\left|\bar{I}_L\right|^2 \qquad (15)$$

Equation (15) makes it clear that FOOB may theoretically reduce the product of recoil stroke and recoil force by a factor of four relative to equation (14). If less than half the momentum is imparted to the cannon prior to firing, the recoil velocity and kinetic energy will be higher after firing. Conversely, if more than half the momentum is imparted prior to firing, the recoil velocity and kinetic energy will be higher prior to firing. Thus, it may be seen that it is ideal to impart half the momentum prior to firing.

Challenges to Implementing FOOB

There are five basic issues with FOOB:

- Ignition variability.
- Misfire.
- Hang-fire.
- Accuracy.
- Mechanism complication.

The first three issues may be considered the major obstacles to weaponization of a FOOB tank gun and will be elaborated upon. The fourth issue, accuracy, is a concern resulting from the obvious potential for the gun barrel and mount to undergo undesirable flexure immediately prior to firing. This will degrade accuracy. Efforts to improve the stability of guns may be useful for FOOB to mitigate this undesirable effect. It is also worth noting that guided ammunition may reduce the reliance upon gun accuracy. The fifth issue is intended to encompass the challenges of loading a gun out of battery, integrating an ignition system that must endure recoil acceleration prior to firing, etc.

Ignition Variability

The variation time between when the "trigger is pulled" and when the bullet starts to move down the bore is of concern for FOOB recoil. The reason is that when the gun is pre-accelerated forward prior to firing, it reaches its maximum design speed just prior to firing. Thus, the cannon may traverse substantial recoil stroke and the kinetic energy will be affected. Application of engineering to address this variability requires that the cannon have extra recoil energy after firing to ensure that it will return to the catch latch. This, in turn, imposes an impact energy burden on the catch latch, while compromising the reduction in peak recoil force. Fortunately, it is anticipated that electrothermal-chemical (ETC) ignition of tank gun ammunition will dramatically reduce this variability to a small fraction of a millisecond. (Experimental results have indicated less than 50 μs of variation (ref 9).) Simulation to be presented in Figure 5 will show the cannon to be moving at 7 mm/ms and it may be appreciated that a fraction of a millimeter is inconsequential.

Misfire

Misfire occurs when a round does not fire when anticipated. For well-maintained tank cannon this is rare, happening perhaps once in 5000 rounds. Nevertheless, its potential is substantial enough to warrant engineering consideration. For a FOOB gun, this presents the problem that the cannon has been endowed with considerable momentum during its pre-acceleration forward. If the round does not fire, the cannon must be brought to rest in a controlled fashion using a misfire snubber. The role of the misfire snubber is analogous to a traditional recoil system operating backwards. It must dissipate the kinetic energy of the pre-accelerated cannon, using reasonable forces. Therefore, it must be provided with some recoil stroke to enable it to bring the cannon to rest.

Using a very conservative approach, we may argue that the greatest permissible snubber forces that could be tolerated would have the same magnitude as the greatest permissible recoil forces. Because the cannon would be pre-accelerated using the greatest permissible recoil forces over the intended recoil stroke, it may be seen that extraction of the kinetic energy imparted will require an equal snubber stroke to bring the cannon back to rest. This argument shows that the intended FOOB recoil stroke could only be half of the recoil stroke that would be employed by a FIB gun. The factor of four reduction in recoil force predicted by equation (15) relative to equation (14) would, therefore, be reduced to a factor of two. This still constitutes an impressive reduction in recoil force.

It may be argued that a greater force magnitude may be tolerated of a misfire snubber. Historical limits to recoil force magnitudes may be altered by the reversed application of the load. For example, the gunner's brow-pad will pull away from his forehead during misfire snubbing. Also, destabilization of the vehicle during recoil (i.e., a tendency to flip it over) would actually be righted by the snubber force. For lack of an appreciation for the recoil tolerance limits of potential future combat system vehicles, it will be postulated that misfire snubber loads may employ forces of twice the magnitude of the intended maximum recoil forces. This will allow the misfire snubber to bring the cannon to rest in half the stroke that it took to pre-accelerate it. This will reduce by one third (not half) the recoil stroke available to a FOOB gun, equation (15), relative to a FIB gun, equation (14). Thus, practical recoil force reductions may be estimated to be a factor of three.

Hang-Fire

Hang-fire is a late firing round. Thus, a hang-fire must be immediately preceded by a misfire. As misfires are rare, hang-fires are even more rare. If a hang-fire occurs after the misfire snubber has returned the cannon to rest, it may be seen that it will endow the cannon with the full kinetic energy of equation (14). Even if an exotic recoil actuation technology (such as magneto-rheological dampers) could be employed to apply a perfect flat force recoil curve to bring the hang-fired cannon to rest, there would be insufficient recoil stroke available to do so without grossly violating the maximum allowed recoil force. For a realistic recoil system, the situation is made worse by the challenges that prevent full recoil forces from being applied. There is no known reasonable solution to accommodate hang-fire without catastrophic failure of the gun and the subsequent potential for harm to the remainder of the combat system.

In the absence of a means to accommodate hang-fire, the focus of engineering effort has shifted to a means to eliminate the potential for hang-fire. (A common rule of thumb for acceptable rates for catastrophic failure is one in a million.) ETC ignition of tank gun ammunition has been identified as a potential means to achieve this objective. ETC uses very high-powered electrical ignition to initiate the charge. The electrical flow path may be reliably short-circuited by the mechanics of a misfire. Further, the propellant to be used by ETC is intended to be a low vulnerability propellant. This means that the propellant will be hard to ignite in the absence of the plasma generated by the ETC process. Thus, the potential for prior hang-fire mechanisms, such as a burning ember, is reduced.

Although there has been no known occurrence of a hang-fire during any of the ETC testing to date, this does not ensure that the chances are in the one in a million range. Therefore, a dedicated effort to examine the potential for ETC to eliminate hang-fire is warranted before embarking on a development program that relies upon its performance to enable FOOB recoil.

NUMERICAL SIMULATION OF GUN RECOIL

The basic principles of FOOB recoil management are best clarified by demonstration. The following figures are based upon an M35 105-mm tank gun designed to implement FOOB juxtaposed by FIB recoil. The FOOB recoil essentially will be provided for by incorporating three elements:

- A catch and release latch at a "home" out-of-battery position.
- Specialized recuperators designed to provide a softer spring rate with a high pre-load.
- Variable orifice hydraulic brakes designed to minimize dissipative friction during the intended recoil stroke, while providing high braking forces in front of the intended firing position (a misfire snubber) and braking behind the latch (a hang-fire snubber).

Because this test fixture is designed as a retrofit to an existing system using 40-year-old ammunition technology, it is considered essential to provide for hang-fire handling. However, because the test gun is only intended to be fired from a hardstand, snubbing forces could be applied that would be unacceptable in a fighting vehicle.

The simulations were conducted using recoil design codes validated for FIB recoil on the M35 and XM291 gun programs. The firing impulse with a perforated muzzle brake is 16,780 N·s (3772 lb_f·s) applied to a recoiling mass of 1090 kg (2400 lb_m).

The ballistic load is first applied using FIB recoil. Subsequently, the motion imparted to the recoiling cannon within the gun mount engages the braking action of the recoil cylinders as shown in Figure 3. (Note, the blow-down momentum imparted after shot-exit is not shown. This simulation assumes a muzzle brake that essentially eliminates any further momentum after shot-exit.)

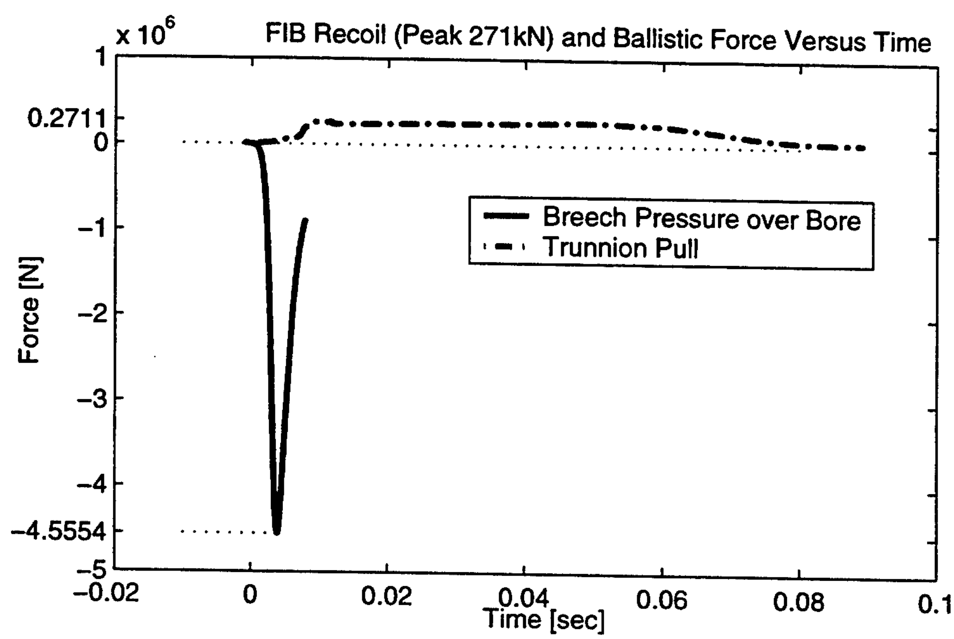

Figure 3. Fire-in-battery (FIB) ballistic and recoil loads versus time.

A peak recoil force of 271 kN is applied despite the peak ballistic force of 4555 kN. This constitutes a factor of 17 reduction provided by the recoil system. Because of the nearly flat recoil force, the duration of the recoil forces does not follow suit and is only a factor 10 longer than the ballistic event.

For FOOB recoil, the recoil forces are applied prior to the firing event in anticipation of the ballistic momentum. This may be seen in Figure 4. This enables the peak recoil load to be reduced to 120 kN or 44% of the FIB recoil load. We believe this is representative of what may be accomplished in a weapon system that employs ETC ammunition that will not hang-fire and whose variability in ignition timing is a small fraction of a millisecond.

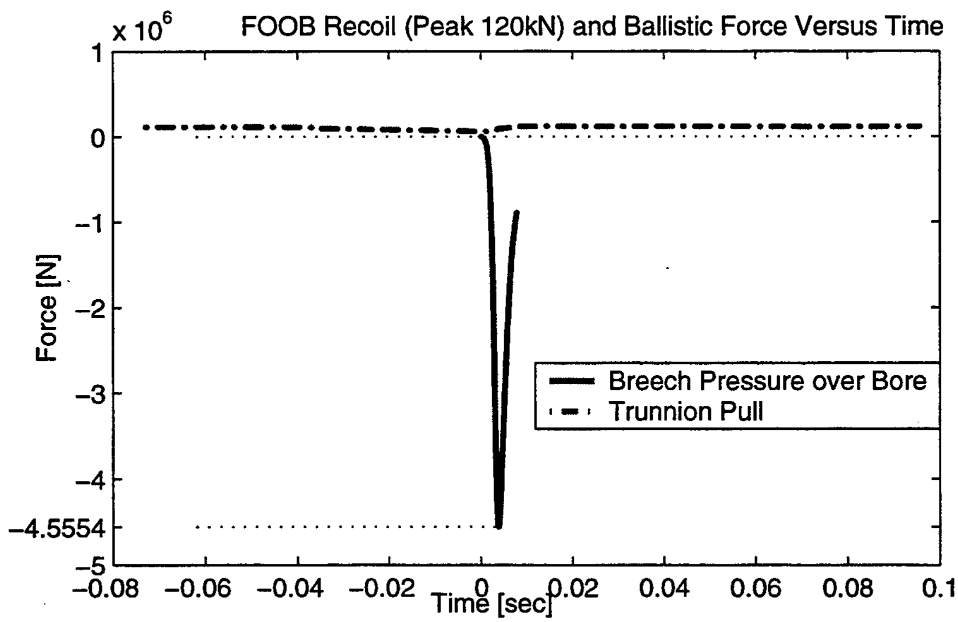

Figure 4. Fire out-of-battery (FOOB) ballistic and recoil loads versus time.

Additional insight may be achieved by comparing the temporal response (momentum) and spatial (energy and phase plane) response of FIB and FOOB systems. This is done in the plots of Figure 5.

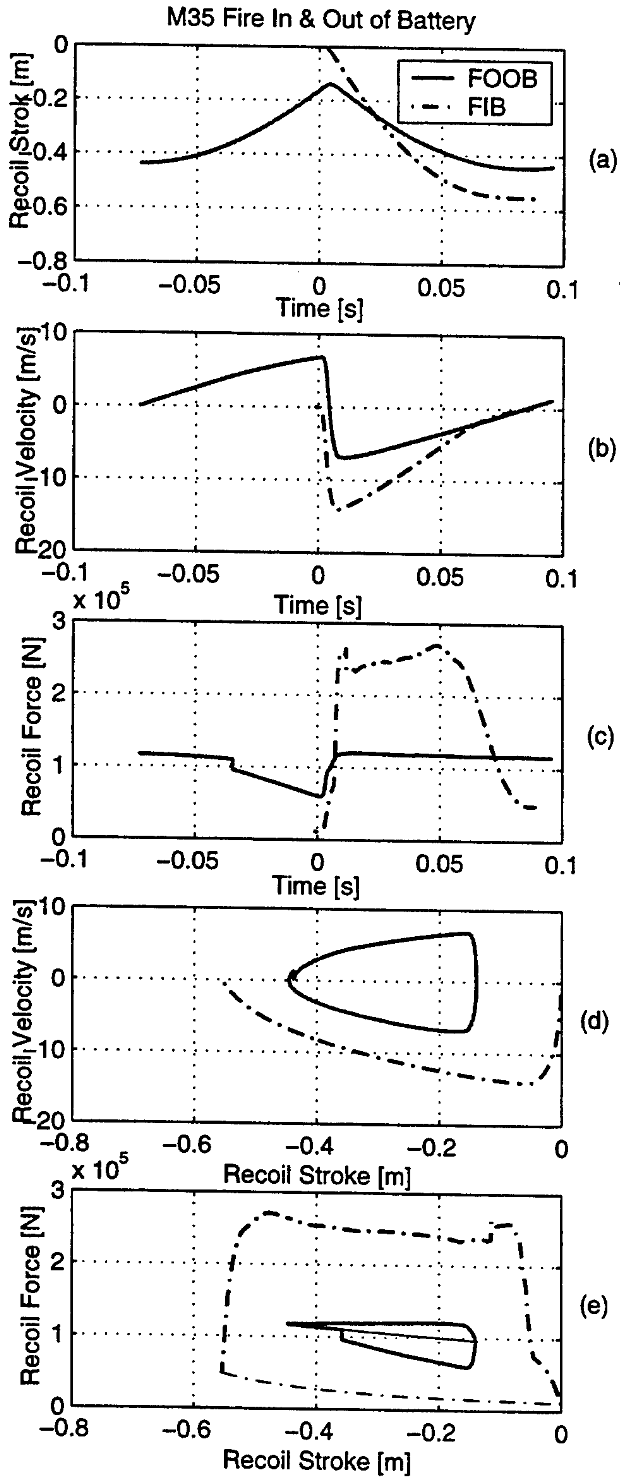

Figure 5. Recoil dynamics.

Figure 5a shows the FIB system beginning its recoil stroke from the zero—in battery—position and then recoiling out to 0.554 m (21.8 inches). The duration of the FIB recoil event is 89 ms. FOOB begins from its latch position at 0.438 m (17¼ inches), then recoils within 0.139 m (5½ inches) of battery before its forward motion is reversed by the ballistic force. It then surpasses the latch position by 7.6 mm (0.3 inch) at 0.446 m from battery before its rearward motion is brought to rest. (The recuperators would then accelerate it forward into the latch.) The duration is 167 ms.

Figure 5b shows FIB starting with zero velocity and then quickly being accelerated rearward by the ballistic force to a speed of 14.0 m/s. The recoil system then brings this rearward motion to rest. The FOOB system begins at rest, and is accelerated forward about 73 ms prior to firing to reach a peak forward velocity of 6.835 m/s. It is subsequently reversed to a rearward velocity of 6.908 m/s by the ballistic forces and is then brought to rest by the recoil system.

Two things are of note here. First, the FOOB cannon is going to be a bit slow at firing. This is to ensure that the rearward velocity imparted is sufficient to send the cannon beyond the latch position after firing. Second, the change in velocity of the cannon is 13.7 m/s. This is 2% lower than for the FIB system. This is caused by the FOOB system imparting momentum to the cannon during the ballistic cycle, whereas the FIB system does not. Figure 5c clarifies this.

Figure 5c reveals the force trajectory with respect to time, the integral of which corresponds to the momentum. For the FIB system, as discussed earlier, the main recoil forces are delayed until the bullet has left the gun for the purposes of accuracy. The variable orifice hydraulic brakes subsequently do an excellent job of maintaining near constant recoil load until the cannon is nearly brought to rest.

Figure 5c also reveals that the FOOB recoil forces diminish prior to firing and then grow. The cause of this is the *undesirable* existence of friction in the system. During the pre-acceleration, friction robs energy from the recuperators that are driving the cannon forward. After reversal of the velocity by the ballistic momentum, the friction and recuperators conspire to achieve a higher force application than the recuperators alone. (The apparent step change in FOOB recoil force of 35 ms prior to firing is the result of the simulated sudden engagement of hydraulic fluids within the brake cylinders.)

Figure 5d is a phase plane representation for the dynamics of FIB and FOOB recoil. This is an interesting perspective for those familiar with state-space and servo control systems.

Figure 5e constitutes the energy domain. The total recoil force for both types of recoil is plotted using a thick line. The recuperator forces are included as a thin line. The area under the total FIB recoil force curve constitutes the kinetic energy of recoil extracted by the recoil cylinders (129 kJ). The recuperator force extends from a slight pre-load of 11 kN in battery to a maximum load of 49 kN at 0.554 m out of battery. The area under this wedge constitutes the energy stored in the potential (spring) energy of the recuperators to return the gun to battery for firing the next round. The area between the total force and recuperator force is dissipated as heat by the brakes. The recoil brakes also dissipate the potential energy of the recuperator during the return to battery (not shown).

The total FOOB recoil force traverses its recoil stroke twice, creating a closed hysteretic loop. The FOOB system first begins at its latch position and then moves forward. The aforementioned friction reduces the force, causing the force travel trajectory to have a pronounced negative slope, with a magnitude lower than that of the recuperator alone. Upon firing, the friction and recuperator forces conspire to maintain a nearly constant force until the cannon is again brought to rest just past its latch position. The area within the loop constitutes the frictional energy lost during recoil. Examination of the recuperator force line clarifies how a highly pre-loaded soft spring may approach a flat travel force profile. However, as this is approached, the peak recoil force just after firing would increase because of friction.

The total recoil energy for this system computed using equation (12) is 129 kJ. FIB recoil force applied over the 0.554-m stroke of Figure 5a is computed as 251 kN using equation (13) and the free-recoil stroke of 39 mm computed in equation (10); it is 233 kN using equation (14). The simulated value of 271 kN of Figures 3, 5c, and 5e is 8 and 16% higher than ideal theory, respectively. The FOOB recoil force is computed as 105 kN using equation (15) over the stroke traversed between –0.438 m and –0.139 m of Figure 5a. The simulated value of 120 kN of Figures 4, 5c, and 5e is 14% higher than the ideal theory.

FOOB RECOIL: A SERVO CONTROL SYSTEM

It is clear from our analysis that modest changes in recoil forces, launch momentum, even gun elevation will have a direct effect on how far the gun must be engineered to overshoot the catch latch to ensure reaching it under a worst case scenario. This overshoot consumes valuable design recoil stroke and imparts greater energy upon the latch during engagement and, thus, requires a more robust or complicated latch. Therefore, methods to control FOOB recoil as a servo control system in analogy to the fire control stabilization of tank guns could be advantageous. In particular, open-loop alteration of the firing time, based upon anticipated momentum, firing angle, and frictional state of the gun, may prove effective at rejecting predictable disturbance loads.

Feedback control would prove essential if unpredictable disturbance loads were compromising performance. Until test fixtures mature, and experience is gained, it is very challenging to anticipate the magnitudes of these disturbances and assess their effect. The simplest feedback system could be applied during the pre-acceleration phase and could fine-tune the firing time based on the actual run-up trajectories, but clearly it could not compensate for disturbances incurred after the ignition delay window just prior to firing.

Feedback control of recoil could be achieved through the application of a control actuator run in parallel with the recoil cylinders. (The requirements of such an actuator would bear some similarity to those of an electromagnetic suspension actuator (ref 10).) Force magnitudes perhaps a few percent of the total forces depicted in Figure 5 could achieve substantial disturbance rejection. The ability of these actuators to apply loads with or against velocity could enable them to do more than just disturbance rejection; they could increase performance by encroaching on the optimal flat recoil force profile with zero hysteresis to the degree their force and power can contribute.

The use of low levels of controlled friction (as provided by magneto-rheological fluidic dampers) could also prove of utility, although they inherently reduce performance.

DISCUSSION AND CONCLUSIONS

Fire out-of-battery recoil may dramatically reduce the recoil forces or recoil stroke, or both, required relative to traditional fire in battery systems. Reduction of peak recoil forces attenuates the shock environment imposed upon the weapon platform (e.g., the gunner's brow pad) and reduces structural requirements for the mount and turret (e.g., enables reduced weight). It may also find application to mitigate the recoil challenges imposed by lightweight cannon structures (e.g., composites) that are intended to reduce armament weight but increase recoil energy.

This conclusion hinges on the requirement that ammunition for weapon systems that employ FOOB proves extremely unlikely to hang-fire (fire late). The ammunition should also exhibit very limited variation in the shot-start delay, to within a fraction of a millisecond. Electrothermal-chemical propulsion has exhibited ignition properties that may enable such ammunition and, thus, enable FOOB recoil.

Friction during the intended operation stroke of a FOOB recoil system detracts from its overall performance. Its propensity to oppose motion dissipates energy and results in increased maximum recoil forces. This is most pronounced during the rearward recoil stroke of FOOB recoil, immediately following velocity reversal.

It is important to note that FOOB does not reduce the recoil momentum imparted to the weapon platform. Therefore, issues of vehicle stability during firing are not substantially improved by employing this recoil management technique. A typical vehicle has its first mode upon its suspension near 1 Hz. FIB momentum applied over 89 ms essentially has a Dirac delta function "impulse" effect on the vehicle response. FOOB's increased duration to 167ms is also largely impulsive to the vehicle—although some limited enhancement may be anticipated. It is interesting to speculate that an active suspension that increases the vehicle's response bandwidth could leverage the increased recoil duration enabled by FOOB to better stabilize the vehicle *during* and after recoil.

REFERENCES

1. Kern, P.J., "Future Combat Systems," *The Defense Advanced Research Projects Agency (DARPA) 21st Systems and Technology Symposium*, Dallas, TX, 6–8 September 2000.
2. Ogorkiewicz, R.M., *Technology of Tanks: Volumes I and II*, Jane's Information Group, Surrey, UK, 1991.
3. Floroff, S., private communication, 18 April 2001.
4. Nerdahl, M.C., and Frantz, J.W., "Mathematical Models for Engineering Analysis and Design of Howitzer," Rock Island Arsenal Technical Report R-RRA-S-3-28-73, May 1973.
5. Burton, L., Hoppel, C., and Kaste, R., "Design Tradeoffs for a Very Lightweight 155-mm Howitzer for the U.S. Army Light Forces," *Proceedings of the 8th U.S. Army Symposium on Gun Dynamics* (G. Pflegl, Ed.), ARCCB-SP-96032, Benet Laboratories, Watervliet Arsenal, NY, 14–16 May 1996, pp. 15.1–25.
6. Gough, P., "The XNOVAKTC Code," U.S. Army BRL-CR-627, Paul Gough Associates, Portsmouth, NH, 1990.
7. Gast, R., "Modal Analysis of the Dynamic Flexure in Tank Weapons by the Uniform Segment Method," Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, NY, May 1988.
8. Heron, B.G., "Required Free Travel of 105mm LR Gun," Engineering Study, FMC Ordnance, San Jose, CA, 22 December 1982.
9. Eldredge, N., private communication, 6 April 2000.
10. Beno, J.H., Bresie, D.A., Guenin, A.M., and Weeks, D.A., "The Design of an Electromagnetic Linear Actuator for an Active Suspension," Publication 1999-01-0730, *SAE International Congress and Exposition*, Detroit, MI, 1–4 March 1999.

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