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RECOIL CONSIDERATIONS FOR RAILGUNS

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The firing of any gun, electromagnetic or otherwise, imparts substantial momentum to the launcher, and ultimately the weapon platform. The objectives of the future combat system program call for similar lethality to a current heavy tank on an extremely lightweight vehicle of nominally twenty tons. Prior experience with the M551 Sheridan, a light tank first put into production by the United States in 1966, raises concern that firing large caliber armaments from light vehicles may result in unacceptable crew discomfort and vehicular reaction during recoil. This report provides a future combat system armament integration perspective for railgun recoil.

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INTRODUCTION

The firing of a large caliber gun imparts substantial momentum and kinetic energy to the projectile. By conservation of momentum, a reaction is applied to the launcher that is equal and opposite to that of the projectile and any other inertia ejected out of the muzzle. For an electromagnetic gun, the sources of momentum, in addition to the projectile, include sabot/armatures, any atmospheric gas pushed out of the gun, and muzzle arc effects. Note that the latter two are negligible for most analyses. As such, the combined mass of the projectile and its sabot/armature is termed the launch mass. For a traditional cannon, the propellant gas momentum must also be considered and may approach that of the launch mass unless muzzle brakes are employed to redirect the exiting gases (ref 1). Forces between and within the mount and cannon during firing, such as recoil brake loads, cable jerk, and muzzle shunt reaction may also be applied, but do not result in net momentum applied to the fighting platform as the action and reaction cancel within the gun system.

THE BASIC EQUATIONS

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, while momentum may be computed as the integral of force over time. By incorporating Newton's second law and integrating, the product of an object's mass and its change in velocity also represents the momentum imparted to it.

$$KE = \frac{1}{2}mv^2 \tag{1}$$

$$E = \int_0^L F\,dx \tag{2}$$

$$F = ma \tag{3}$$

$$I = \int_0^{t_f} F\,dt = \int_0^{t_f} (ma)\,dt \tag{4}$$

$$I = m\left(v\big|_{t=t_f} - v\big|_{t=0}\right) \tag{5}$$

where

KE is the kinetic energy of the object.
m is the mass of the object (assumed constant).
v is the velocity of the object.
E is energy.
F is the applied force.
L is the travel length over which the force is applied.
I is the momentum imparted.
t is time.
t_f is the duration of the event.
a is the acceleration of the object.

In the case of determining the muzzle energy of a launch mass, equation (2) is used with the ballistic force applied over the traverse of the gun. It is worthy to note that a subtle assumption is often made in computing the muzzle energy using equation (2). The assumption is that the launcher recoils so little during launch, there is a negligible difference between the launch length relative to the recoiling gun and an earth inertial reference frame. In fact, the recoiling gun will pull away from the projectile during launch, decreasing the effective launch length by a percentage equivalent to the ratio of launch mass to the effective mass that recoils with the cannon, when no significant external forces are applied to the gun. This motion of the recoiling cannon becomes manifest as its kinetic energy of recoil. The reduction in muzzle velocity is discernible, but does not have a substantial effect on ballistic performance for realistic gun systems. Management of this recoil momentum and energy, and its effects on the fighting vehicle, are critical to the infield success of any future combat system.

A SIMPLE RAILGUN EXAMPLE

The ability of railguns to achieve a relatively flat ballistic curve (as measured by the piezometric efficiency) is one of their major advantages. If a flat force curve is assumed, the computations of equations (2) and (4) become trivial (integrals of rectangular regions), providing a simple means to gain some perspectives on the forces involved. To achieve a muzzle energy of 10 MJ using a 5-m railgun will result in forces of 2000 kN using equation (2). A 5-kg launch mass would be imparted with a muzzle velocity of 2000 m/s using equation (1). Using equation (5), 10,000 Ns of momentum would result. Therefore, the duration of launch would be 5-ms using equation (4). The results of this example are cataloged in Table 1, along with the computation for a faster projectile and a slower indirect fire round that must carry a heavy ordnance payload.

Table 1. Example Gun Parameters

	Direct Fire Rounds		Indirect Fire Round
Launch Mass (kg)	5	5	20
Muzzle Velocity (m/s)	2000	2500	1000
Muzzle Energy (MJ)	10	15.625	10
Launcher Length (m)	5	5	5
Ballistic Force (kN)	2000	3125	2000
Launch Momentum (Ns)	10,000	12,500	20,000
Launch Duration (ms)	5	4	10

Rigid mounting of such a gun firing a 5-kg round at 2000 m/s would exert a loading of nearly 10 gee's to the hull of a 20,000-kg vehicle for the 5-ms duration of launch. Although the United States attempted to rigidly mount a 90-mm gas cannon to the T95 tank in the late 1950s, such an approach is considered "highly questionable" (ref 2). From a ballistic perspective, the advantage of rigid mounting is that the entire hull mass contributes to the recoiling mass of the gun. This minimizes the kinetic energy of the recoiling parts and simplifies the mount. (In practice, compliance of the mount to vehicle interface will prevent a truly rigid mount and would need to be accounted for in the design.) From a system perspective, rigid mounting applies a substantial shock loading to the vehicle, its contents, and crew. It is desirable to provide shock isolation between the recoiling cannon and the vehicle while minimizing the intrusion of the recoiling cannon within the turret of the vehicle. This is the function of the gun recoil system.

WHERE IS THE RECOIL FORCE MANIFEST DURING LAUNCH?

A common area of confusion and discussion regarding recoil of railguns centers around two schools of thought on just where the reaction force of launch is applied to the cannon. One school of thought argues that the recoil force is exerted at the breech of the railgun (ref 3). The other, most notably championed by P. Graneau, argues that the recoil forces are manifest along the rails near the armature (ref 4). (Coilgun recoil is not subject to any confusion. The reaction occurs at the same coils that provide propulsion, in close proximity to the armature [ref 5].)

Those wishing to resolve the apparent paradox of railgun recoil for themselves need only consult a basic textbook in fundamental physics (such as Reference 6: volume two, section 27) to learn that electromagnetic fields themselves carry momentum. This fact is required for the simple application of the Biot-Savart law to two charged particles traveling through space in order for their reactions to satisfy Newton's third law: conservation of momentum (ref 7).

The allure of Graneau to unwitting engineers is that he provides a comfortable means to visualize continuity of momentum within the single-turn, current loop of a simple railgun. Mathematicians (ref 8) and experimentalists (ref 9) have demonstrated that under complete integration of the current loop, the reaction occurs at the breech. However, this provides little solace to those uncomfortable with the concept of rails near the armature pushing it while the reaction is to occur at the breech, which is a direct consequence of an element-by-element interpretation of the Biot-Savart law.

Consulting Feynman et al. (ref 6), who elegantly provide comfort that momentum must be locally conserved, may restore solace. Therefore, it is the fields that *communicate* the momentum from the armature to the breech. Misunderstanding of the field momentum by engineers has been attributed to an unfortunate means of undergraduate instruction based on "action at a distance" with calls for revising the pedagogical approach (ref 10).

The bottom line, recoil momentum for a railgun is manifest at the breech. However, some tension will be applied to the rails caused as the current migrates inward from a distribution within and upon the surface of the rail conductor before it crosses the plane of the inner rail surface at the breech and armature. As the current bends in, the magnetic forces will push it out—with a discernible axial component. This axial tension shared between both rails of a one-turn railgun will have a magnitude roughly approximate to the ballistic force multiplied by the ratio of the width of one rail to the armature width, increasing if the mid-span current density centroid tends toward the outer rail surface.

THE ROLE OF A RECOIL SYSTEM

Recoil systems are incorporated to act as shock isolators between the recoiling parts of the cannon and the vehicle hull, thus reducing the magnitude of the forces exerted upon the vehicle while increasing their duration to achieve conservation of momentum.

Current direct fire gun design philosophy is to minimize any recoil forces applied to the cannon, until shot exit has been achieved. Thus, one may consider the cannon to be firing in free space for the purpose of computing the recoil velocity using equations (4) and (5). For guns that do not delay applied recoil forces, the free recoil velocity assumption is not substantially compromised, since the recoil system loads are typically an order of magnitude lower than ballistic forces.

The principal design goal of a recoil system is to minimize the maximum magnitude of the recoil forces applied to the vehicle using the available recoil stroke. The optimum force is therefore a flat force profile. This force profile is often achieved through a combination of recuperators (gas springs) and variable annular orifice hydraulic brakes. This force is commonly termed the trunnion load as it is applied through the trunnion bearings of the gun mount to the vehicle.

For turreted vehicles, recoil stroke is limited because it consumes a swept volume (for any elevation) within the armored vehicle. Under-armor volume is a precious commodity, and the cost of supporting that armor severely restricts the recoil stroke that can be made available. For external or pedestal mount guns, no such restriction on recoil stroke exists, but the extended cradle and mount requirements and challenges allowing a cannon to recoil when elevated limit the practical design space. For electromagnetic guns, bussing the electrical supply from the pulse-forming-network to the recoiling cannon will prove to be a primary consideration.

Other recoil system engineering considerations include the need to quickly return the gun to its starting position, termed "return to battery," dissipation of the heat from the recoil brakes, and performance when firing a variety of rounds of different launch momenta.

A RECOIL EXAMPLE

Let's assume that the recoiling cannon mass is 1000 kg, 0.5-m is available for the recoil stroke (*after shot exit*), the 5-kg, 2000 m/s round of Table 1 is fired, and the trunnion load is flat. Using equation (5), the rearward recoiling velocity will be 10 m/s (assuming the cannon is initially at rest). Then 50 kJ of kinetic energy recoil may be computed using equation (1). A trunnion load of 100 kN may be computed using equation (2). The duration of recoil will be 100-ms using the equality of equation (4). This example is included in Table 2, along with a 2000 kg gun for the three rounds considered in Table 1. (*In-bore free recoil would be just under 25-mm for this configuration.*)

Table 2. Example Recoil Systems

Launch Momentum (Ns)	10,000	10,000	12,500	12,500	20,000	20,000
Recoiling Mass (kg)	1000	2000	1000	2000	1000	2000
Recoiling Velocity (m/s)	10	5	12.5	6.25	20	10
Recoil Kinetic Energy (J)	50,000	25,000	78,125	39,062.5	200,000	100,000
Recoil Stroke (m)	0.5	0.5	0.5	0.5	0.5	0.5
Trunnion Load (kN)	100	50	156.25	78.125	400	200

RECOIL TOLERANCE GUIDELINES

Recoil Acceleration of Hull

A clear metric of the severity of recoil is the acceleration of the hull realized by the applied trunnion load.† This applies a D'Alembert loading to all contents of the hull that are rigidly attached using equation (3). The metric is not of great utility because compliance of components mounted to the hull plays a substantial role in how much energy is imparted. Crew performance is also a substantial function of the ergonomics of the man-machine interface. Hull accelerations may become an issue as they exceed one gee. Performance degradation (e.g., *flinching*) may become intolerable as hull accelerations approach two gee, but this must be considered on a case-by-case basis. The hull accelerations for the systems of Table 2 are listed in Table 3.

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† The hull acceleration is complicated by the fact that all cannons are mounted above the hull's center of mass to provide for firing in defilade. This offset results in a moment arm between the centerline of the cannon and the center of mass of the hull, and results in combined lateral and rotational momentum imparted during firing. This moment couple must be accounted for, but detracts from the simplicity of the presentation and therefore will not be considered further.

Table 3. Example Recoil Metrics for Examples from Tables 1 and 2

Launch Momentum (Ns)	10,000	10,000	12,500	12,500	20,000	20,000
Ballistic Force (mN)	2	2	3.125	3.125	2	2
Recoiling Mass (kg)	1000	2000	1000	2000	1000	2000
Trunnion Load (N)	100,000	50,000	156,250	78,125	400,000	200,000
Recoil Duration (ms)	100	200	80	160	50	100
Acceleration of Vehicle (m/s^2) [gee]	5 [0.51]	2.5 [0.25]	7.81 [0.80]	3.91 [0.40]	20 [2.04]	10 [1.02]
Characteristic Frequency (Hz)	5	2.5	6.25	3.125	10	3.125
Ogorkiewicz Ratio (Ns/metric-ton)	500	500	625	625	1000	1000
Shock Severity ($m^{(5/2)}/s^{(3/2)}$)	5.59	1.98	13.6	4.84	89.4	31.6
Cannon Acceleration (m/s^2) [gee]	2000 [204]	1000 [102]	3125 [319]	1562.5 [159]	2000 [204]	1000 [102]

Future ground combat system vehicle concepts that include a manned mobility pod with an articulated armament mobility pod may cut the effective hull inertia of these twenty-ton systems to ten tons (ref 11). This would double the recoil acceleration, and completely alter the recoil tolerance of the armament pod. The incorporation of extreme muzzle brakes in the articulated Swiss UDES-XX-20 tank destroyer would be indicative of recoil challenges for this configuration (ref 2).

Minimized Shock Loading Bandwidth

A second and often unconsidered goal of the recoil system is to minimize the bandwidth of the load spectrum applied to the vehicle. If one were to envision the recoil load pulse as resembling that of a half sine wave, it may be seen that it is challenging to excite vibrations higher than the frequency of the wave, which is the inverse of double the recoil duration. This may be termed the characteristic frequency, f_c, of recoil. Components structurally mounted with fundamental modes far above f_c may be considered rigid, while the receptance of structures with lower modes—such as ammunition magazines and autoloader mechanisms—may be substantial and prove sensitive to load orientation and operational state.

In general, the lower this frequency, the greater the portion of recoil energy that will simply be dissipated by the suspension system and not become manifest as subcomponent vibration. Strictly speaking, an ideal flat force trajectory recoil profile (*boxcar window*) would have a 3-dB main lobe bandwidth 70% higher than f_c, with a peak side-lobe dB of –13 (ref 12).

Ogorkiewicz's Ratio

The most often cited reference to the recoil tolerance limit of fighting vehicles is published by Ogorkiewicz (ref 2). The ratio of recoil momentum (often termed "impulse") to vehicle mass should not exceed 900 Newton seconds per metric ton. This is a "rough empirical rule" that does not accurately reflect the effects of unusual design parameters upon recoil tolerance. For example, doubling the recoiling mass of the cannon would have little effect on this ratio, yet it would reduce the trunnion load by half. The launch momentum-to-vehicle mass ratios are listed in Table 3. Note that slow heavy payload rounds, such as those typically fired by a howitzer, constitute a recoil challenge. This is one reason why howitzers do not fire-on-the-move, and may emplace spades to directly couple the vehicle to the earth.

Shock Severity Index

Current practice in fighting vehicle design is that the gunner applies his forehead to a brow pad as he looks through the sight while tracking the target. Substantial body force may be applied to the controls and brow pad to enable the gunner to remain steady while the vehicle traverses rough terrain. Upon firing, his forehead is subject to the jerk of the recoil acceleration of the hull. It is well-known that firing the heat round out of the M551 Sheridan was uncomfortable to the crew, with an Ogorkiewicz ratio in excess of 1000 Ns/ton. (Stories of gunners receiving black eyes during firing are common.) While it may seem that the use of a brow pad may be eliminated in favor of a more modern input device, the current system works well. It is also likely that the application of substantial body force reduces any unsteadiness caused by the duress imposed upon a gunner while engaged in battle. Further, a severity index of human response to gee loading may prove reasonable for assessing the trend of shock severity imposed upon other systems within the fighting vehicle.

A shock severity index of human response to impacts lasting between 10 ms and 1 second has been developed in an attempt to quantify human tolerance to automotive crashes. The findings from the Society of Automotive Engineers have resulted in a severity index based upon a weighted integral of acceleration over the duration of the impact event (ref 13).

$$SI = \int_0^{t_f} a^n dt \qquad (6)$$

where

SI is the severity index.
a is the imposed acceleration.
n is an empirical weighting factor greater than one
(2.5 for head face impacts).
t_f is the duration of the event.

This astute observation—correlating recoil shock severity to automotive crash testing—made by B. G. Heron (ref 14), allows for the prediction of recoil shock severity for future fighting vehicles outside of the empirical design space upon which Ogorkiewicz's ratio is based.

Acceleration of Cannon

The rearward acceleration of the cannon during the free recoil driven by the ballistic force is very large. The reaction force is manifest at the breech, pulling the inertia of the cantilevered launcher rearward and placing the entire launcher structure in a substantial state of tension that is a maximum at the breech, and vanishes at the muzzle. This loading, along with projectile interaction loads, also drives the nonlinear gun-whip dynamic during launch and is further exacerbated by any lack of axial symmetry of the distribution of inertia and rigidity along the launcher (ref 5).

A common developmental challenge for traditional cannons is the failure of the thermal shroud and bore evacuator assembly to survive this combined loading. Experience in the application of composite support structures to traditional cannons has also resulted in challenges manifest as a delamination under the combined effects of rearward acceleration, gun-whip, and bore dilation.

The severity of the shock environment of the launcher cannot be overstated. This is particularly true for muzzle-mounted devices that are subject to the greatest gun-whip activity and impose their D'Alembert loading along the entire length of the launcher structure (refs 15,16). Good advice is to recoil as much inertia as possible at the rear of the cannon, but bear in mind this inertia will receive tremendous mechanical shock. For example, the more massive side of the recoil brake cylinders is coupled to the recoiling cannon for the M35 105-mm and XM291 120-mm and 140-mm tank gun designs. The benefits of incorporating some portion of the power supply inertia with the cannon must be weighed against the challenges that may ensue in this shock environment.

NONTRADITIONAL RECOIL DESIGN OPTIONS

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 (5) and (1), it may be determined 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 fire-out-of-battery is that the recoil stroke and/or trunnion load may be dramatically reduced. Holding one constant, the other may be reduced by a factor of four. For railguns this could be applied to reduce recoil stroke and ease the incorporation of an elastic contact—as opposed to a slide contact—between the power supply and the rails. Disadvantages of fire-out-of-battery include misfire and hang-fire handling, the latter of which is not a likely problem for a railgun. Incorporation of misfire handling reduces the practicable reductions to a factor of two or three.

The Davis Gun

Named for the inventor of such a gun during the Great War by Commander Clelland Davis of the United States Navy, a Davis gun eliminates recoil momentum by firing an ordnance projectile forward and a dummy projectile rearward out of a common cannon barrel and chamber (ref 17). Efforts have been undertaken to apply such cannons to aircraft, shoulder-fired cannons, and even spacecraft. The challenges of loading such a cannon make the engineering requirements for a reloadable Davis gun prohibitive for most applications. The chamberless nature of an electromagnetic cannon is an intriguing advantage to a Davis railgun. However, the energy lost to and increased ammunition requirements for the dummy projectile are likely to leave the Davis railgun an armament engineer's curiosity for a ground combat vehicle.

Double Recoil

Double recoil is a technique not uncommon for heavy guns, including the German 21-cm Kanone 12 in Eisenbahnlafette that bombarded portions of Kent from the French side of the English Channel in the summer of 1940 (ref 18). The 280-mm atomic gun fielded by the U.S. in the early 1950s is another example of a double recoil gun.

Double recoil simply introduces an intermediate sprung mass between the recoiling cannon and the hull. Two recoil systems are used to bring the cannon to rest. The primary recoil couples the recoiling cannon to the intermediate mass typically using hydropneumatic cylinders. Once endowed with some portion of the cannon momentum, the motion of the intermediate mass is coupled to the hull via the secondary recoil system. Using this arrangement, the intermediate mass is shock-isolated from the ballistic force by the primary recoil system, yet its inertia will lower the energy imparted to the vehicle through the secondary recoil system. (Reference 19 provides guidance on double recoil system design.)

A double recoil system for a railgun may provide a more benign shock environment to leverage other system inertia (such as the power supply) to mitigate recoil. Although the gee loading of the intermediate mass would be much lower than if it were directly coupled to the cannon, it may still prove challenging to endure.

Sabot Catcher

Any worthy and creative armament engineer has attempted to consider means to recapture the kinetic energy endowed upon the sabot/armature and impart it to the projectile. This is challenging to implement for many reasons, including what could be termed a second stage armature to deliver the captured energy to the projectile. If this second stage propulsion were abandoned, simply slowing down the armature—while allowing the projectile to continue on unimpeded—would be far less challenging. Engineering a muzzle shunt to favorably interact with the armature to achieve recoil reduction is an intriguing possibility; but is complicated by the length required to slow down the high-speed armature using reasonable forces.

Inertial Breech (ref 20)

One means of totally changing how recoil is manifest within the cannon is to allow the breech to slide freely within the rails. This eliminates the recoil acceleration imposed upon the remainder of the launcher. However, recoiling mass is dramatically reduced. Combined with fire-out-of-battery or double recoil, the inertial breech may provide an interesting alternative if acceleration of the rail structure is presenting a major obstacle.

Spades

Spades may be deployed to directly couple much of the recoil momentum through the hull to earth-ground during recoil. This approach is commonly used for towed howitzers. Although fire-on-the-move is always a desired capability, Table 1 makes it clear that it is the indirect fire rounds that represent the greatest challenge to electromagnetic gun recoil. Most typically, indirect fire rounds would only be fired when a combat vehicle is not anticipating concurrent engagement with an enemy fire, thus, shoot-and-scoot spade deployment may be viable.

Active Recoil Mitigation Suspension (ref 21)

It is conceivable that the recoil tolerance of future ground combat systems could be enhanced through the application of an active suspension that is specifically designed to handle the predictable recoil disturbance of firing. For example, the suspension control law might be able to emulate a suspension lockout, even while the vehicle is traversing terrain. The effect would be the direct coupling of some recoil momentum to earth-ground and the subsequent reduction of hull acceleration loads. This would improve both the Ogorkiewicz ratio and shock severity index. Such a goal becomes viable as the bandwidth of the active suspension increases to intersect the bandwidth of the recoil trunnion loads. This is facilitated by recoil techniques to reduce trunnion load and increase recoil duration, thus lowering the bandwidth of recoil as indicated by the characteristic frequency, f_c.

Electromagnetic Recoil Actuators

An alternative to the use of recuperators and hydraulic recoil brakes is the use of electromagnetic actuators. Such systems offer the potential to eliminate the use of undesirable hydraulic fluids in an all-electric vehicle. Further, the potential to recapture the kinetic energy of recoil may be exploited. The engineer considering this potential is cautioned to examine the relatively puny energy available and weigh the burdens of trying to capture it accordingly. The use of such actuators for fire-out-of-battery recoil is highly promising, particularly if used in parallel with a recuperator (ref 22).

CONCLUSIONS

The application of large caliber armament to light fighting vehicles represents a design challenge to system integration. Recoil tolerance of such vehicles is historically low. Simple physics-based methods of estimating the basic recoil system parameters have been presented. Recoil tolerance metrics have been provided in an attempt to predict the acceptability of a recoil system design for a future combat system. It has been shown that relatively slow, but heavy indirect fire rounds may prove a recoil challenge. Caution is to be exercised when using empirically-based tolerance metrics as they do not account for novel system integration techniques that may increase the recoil tolerance of future combat systems.

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