Design Considerations for an Electromagnetic Railgun to Be Used Against Antiship Missiles

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Design Considerations for an Electromagnetic Railgun to be used against Anti-Ship Missiles

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Abstract—**Railguns can reach higher muzzle velocities and fire rates than conventional guns. Muzzle velocities up to 2400 m/s and fire rates of more than 50 Hz have already been demonstrated with projectiles having a mass of 140 g and a square calibre of 25 mm^2. We investigated if a Close In Weapon System (CIWS) based on a railgun performs better against incoming anti-ship missiles than a conventional CIWS such as the Goalkeeper. CIWS are operational systems that defend a ship against incoming subsonic anti-ship missiles. However, future anti-ship missiles will be supersonic and more difficult to defeat with conventional gun systems. Railguns are expected to perform better against these future threats thanks to their higher muzzle velocity and fire rate. We developed a simulation model calculating the hit probability of a burst of projectiles fired with muzzle velocities ranging from 1200 m/s to 2400 m/s and fire rates ranging from 75 rounds per second to 300 rounds per second. The target velocity ranges from subsonic (300 m/s) to supersonic (600 m/s). The performance requirements for a corresponding railgun are used to discuss possible system layouts. In general, the kinetic energy to be delivered by the launcher translates into requirements for the pulsed power supply. However, thermal management has to be considered for repetitive launching. Therefore, we carried out numerical simulations on the electrical and thermal behaviour of various solutions and compare their advantages and drawbacks.**

Index Terms—**Railgun, parallel augmented railgun, system study, pulsed power, hypervelocity, simulation.**

I. Introduction

The defense of ships against anti-ship missiles is a great challenge, as little time is available for interception. Indeed, the so-called sea-skimmers fly as close as possible to the sea surface and therefore they are very difficult to detect. The detection ranges can be as low as some kilometers, depending on the speed and the trajectory of the missile. An effective defense requires a dedicated system, the Close-In Weapon System or CIWS.

CIWS are typically semi- or full autonomous, meaning that they are equipped with their own surveillance and tracking radars and that they can decide whether to fire or not with minimal human supervision. This allows for a short reaction time and thus a good efficiency against anti-ship missiles. However, while today's sea-skimmers operate at subsonic cruising speeds, future missiles will be able to approach ships with supersonic speed leaving even less reaction time to their CIWS. Therefore, the question arises, how CIWS could be improved and in this work we analyze the use of electromagnetic acceleration technology.

In the first part of the paper, the efficiency of CIWS against subsonic and supersonic anti-ship missiles will be evaluated. We are using as a basis for our analysis the Goalkeeper, a Dutch WIS. It fires armor piercing projectiles with a mass of 350 g and a muzzle velocity of 1200 m/s, typically in bursts of 300 projectiles with a fire rate of 75 rounds per second or 75 Hz. We evaluate its efficiency against both types of targets, and then widen the investigation using different scenarios characterized by varying muzzle velocities and fire rates of the CIWS. This parametric analysis allows to define conditions to be met by a future CIWS.

In the second part of the paper it is investigated, if an electromagnetic railgun would offer a solution for improving existing CIWS. The theoretical analysis is based on an existing system, ISL's rapid fire railgun RAFIRA [2, 3] and extends to future solutions. Such solutions will require new developments in the field of the corresponding power supply and particular attention is paid to this aspect.

II. Optimal Solutions against Subsonic and Supersonic Targets

A. Description of the Simulation Model

We assume that the anti-ship missile is heading straight to the CIWS and that the projectiles are normally distributed, centered on the longitudinal axis of the missile and with standard deviation σ. In this case, the section S of the target is circular and the single shot hit probability (SSHP) can be calculated with (1).

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$$SSHP = \int_S \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) dr \qquad (1)$$

We assume that the standard deviation σ is the sum of two terms (2). The first one takes into account the ballistic dispersion and varies with the range. The second term is based on the atmospheric dispersion and is a function of the flight time of the projectile.

Fig. 1. Open fire range and kill range

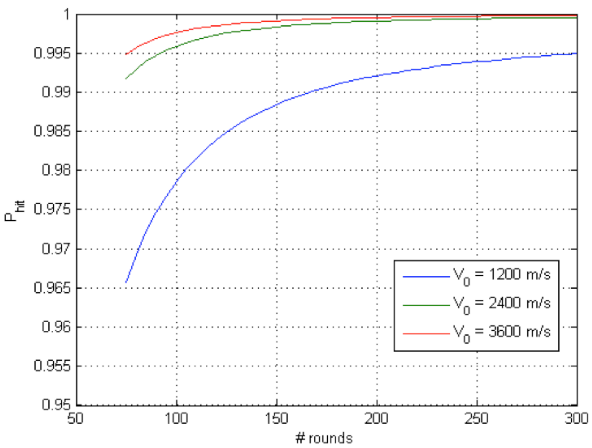

Fig. 2. Hit probability against subsonic targets (300 m/s).

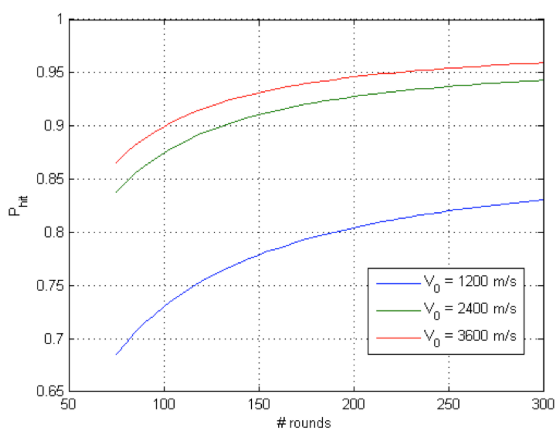

Fig. 3. Hit probability against supersonic targets (600 m/s).

$$\sigma^2 = \left(R\sigma_{ball}\right)^2 + \left(t_f \sigma_{atm}\right)^2 \qquad (2)$$

We use in the simulations typical values: σ_{ball} = 1 mrad and σ_{atm} = 1 m/s. We assume that a hit equals a kill, thus that the kill probability equals the hit probability. The hit probability of a burst is calculated by accumulating the SSHP. A CIWS is considered to be effective if the hit probability equals or is higher than 0.95.

The incoming missile must be destroyed at a certain distance from the ship (the "kill range") such that the debris of the incoming missile doesn't impact on the target (Fig. 1). If we assume that the missile is flying at an altitude of 10 m and that the trajectory of the debris is parabolic, the kill range for a

TABLE I
HIT PROBABILITY OF A CIWS AGAINST SUBSONIC TARGETS

Scenarios		**Gun performance against subsonic targets (300 m/s)**		
V_0 (m/s)	**Fire rate (Hz)**	***# rounds***	***Open fire range (m)***	***P_{hit}***
1200	75	153	1036	0.95
1200	150	88	602	0.95
1200	225	78	531	0.95
1200	300	73	500	0.95
1800	75	85	764	0.95
1800	150	61	548	0.95
1800	225	56	501	0.95
1800	300	54	481	0.95
2400	75	70	704	0.95
2400	150	53	532	0.95
2400	225	49	492	0.95
2400	300	47	474	0.95

subsonic target (300 m/s) is 428 m, and in case of a supersonic target (600 m/s) 856 m. The open fire range will depend on the kill range, the fire rate and the muzzle velocity of the projectiles.

Figure 2 shows the hit probability of a CIWS with varying muzzle velocity and number of rounds against subsonic targets (300 m/s). It is clear that this target can be destroyed with existing CIWS (1200 m/s, 75 Hz).

When we apply the same settings to a CIWS intercepting a supersonic target (600 m/s), Fig. 3 shows clearly that the today's solution is not effective anymore. Only if the muzzle velocity attains 3600 m/s, the hit probability is greater than 95 % with a maximum number of rounds of 300. However, a muzzle velocity of 3600 m/s is not realistic for projectiles flying at low altitudes because of the aerodynamic heating. In order to attain a hit probability of 95 % with a muzzle velocity of 2400 m/s, more rounds should be fired and /or the fire rate should be increased.

B. Subsonic Targets

Table I shows the results of the simulation of the efficiency of a CIWS for muzzle velocities ranging between 1200 m/s and 2400 m/s and for fires ranges between 75 Hz and 300 Hz. It is not surprising that in all cases, a hit probability of 95 % is attained.

An increasing fire rate leads to a decreasing number of rounds required to kill the target. This is due to the fact that the CIWS will open fire only just before the missile would hit the ship, since the SSHP is inversely proportional to the range. Each round being more effective means that a smaller number of rounds will be fired to kill the missile.

Since a higher muzzle velocity implies a smaller flight time and thus a smaller dispersion, fewer projectiles will be required.

TABLE II
HIT PROBABILITY OF A CIWS AGAINST SUPERSONIC TARGETS

Scenarios		**Gun performance against supersonic targets (600 m/s)**		
V_0 (m/s)	**Fire rate (Hz)**	***# rounds***	***Open fire range (m)***	***P_{hit}***
1200	75	5000		0.64
1200	150	5000		0.87
1200	225	2900	8588	0.95
1200	300	711	2277	0.95
1800	75	5000		0.77
1800	150	5000		0.94
1800	225	501	2190	0.95
1800	300	357	1569	0.95
2400	75	5000		0.83
2400	150	917	4521	0.95
2400	225	370	1841	0.95
2400	300	286	1427	0.95

Thus, even if a conventional CIWS (1200 m/s, 75 Hz) is effective against subsonic targets, a CIWS with a higher muzzle velocity and/or a higher fire rate will be more efficient, since it will consume fewer rounds to destroy the target.

C. *Supersonic Targets*

The conventional CIWS is not efficient against supersonic targets. Even if 5000 rounds are fired, the hit probability is only 64 % (Table II). Increasing the fire rate up to 300 Hz leads to a solution, but still requires a large number of rounds (711). It is therefore interesting to increase the muzzle velocity. A CIWS firing at 2400 m/s and 300 Hz, is effective against supersonic targets with an acceptable number of rounds (286, which is less than the nominal burst of 300 rounds).

In the second part of the paper, we will investigate if this novel CIWS is feasible, more specifically when using an electromagnetic launcher.

III. AN ELECTROMAGNETIC ACCELERATOR FOR ANTI-SHIP MISSILE SCENARIOS

The ISL has built up a multishot railgun named RAFIRA (Rapid Fire Railgun) [2, 3] in order to investigate the potential of railgun technology for anti-ship missile scenarios. A railgun is well-known to be the only type of linear electromagnetic accelerator being able to achieve velocities and kinetic energies as required for the scenarios discussed in the previous section. The RAFIRA project shows that using railgun technology allows obtaining fire rates of about 50 Hz [3], which is obtained by classical guns only using multiple barrels (Gatling principle). In the following, it is briefly explained, how RAFIRA operates. In Fig. 4 the loading technique is sketched. The two vertical rails on the right hand side of Fig. 4 belong to the main launcher, whereas the horizontal rails on

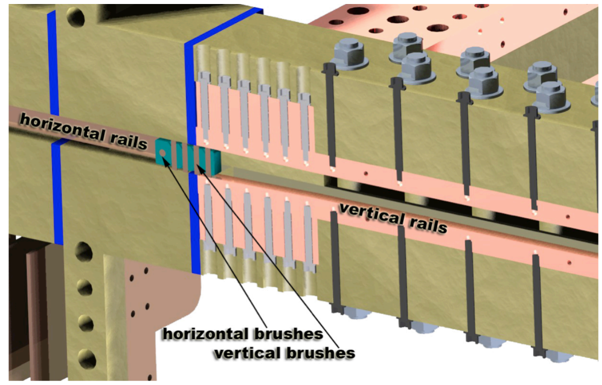

Fig. 4. Loading technique of RAFIRA [2].

TABLE III
PARAMETERS ENTERING PSPICE SIMULATIONS

Capacitor	0,865 µF
Mass of projectile	350 g
Resistance gradient of rails	0,03 mΩ/m
Inductance gradient of rails	0,5 µH/m

the left hand side belong to the loader. The metal fiber brush armature technology developed at ISL allows using a railgun-type of loader using the horizontal armature (brush) in the rear part of the projectile for loading. The four front armatures are designed to carry the current in the main launcher.

While the launcher has recently shown great potential for multishot applications, it is the purpose of this paper to discuss its limitations and to outline future options. The major practical limitation of RAFIRA as of today is the available primary electric energy. RAFIRA is driven by a capacitive power supply with a maximum stored energy of 2.7 MJ. A first improvement would be to couple RAFIRA with the 10 MJ installation of ISL currently feeding ISL's most powerful accelerator PEGASUS [4]. This option is taken as a base for further considerations in this work. On a more theoretical level, two main limitations for multishot operations are to be named: rail heating will limit the number of shots in a salvo and the fire rate is limited by the projectile dynamics and can also be limited by the inertia of the magnetic field. The first phenomenon is well known from repetitive launchers and needs particular attention for the case treated here. The second needs a comment: after a projectile exits a railgun, some current (or magnetic field) can remain in the launcher. The start time of the next projectile depends on the duration of the dissipation (or recovery) of stored residual magnetic energy.

IV. PSPICE SIMULATIONS: RAFIRA AND ANTI-MISSILE SCENARIOS

Having presented RAFIRA and laid out some limitations in the preceding section, it is the purpose of this section to check, if RAFIRA would offer solutions for the scenarios discussed above (Tables I and II). To this end, the PSPICE code was used, which allows coupling the projectile dynamics with the

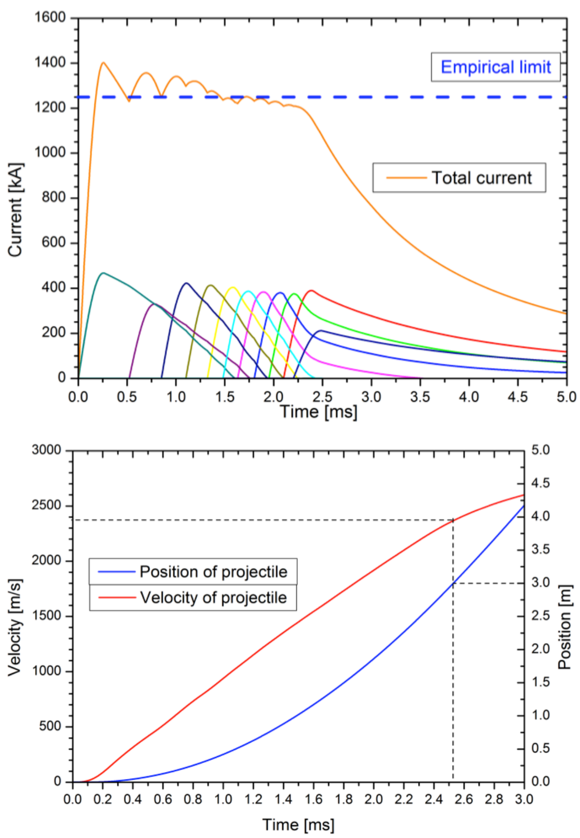

Fig. 5. Results of PSPICE simulation of RAFIRA for the case v = 2400 m/s.

electric circuit equations [5]. Table III gives specific parameters concerning the dynamics of the projectile and the available energy used for the PSPICE simulations and Fig. 5 shows the results for the most ambitious case with v_0 = 2400 m/s. The upper graph shows the total electrical current determining the accelerating force. The highly modular 10 MJ supply (200 x 50 kJ) of ISL allows to form a relatively flat profile peaking at about 1.4 MA. The blue line indicates another empirical limitation to be considered, when designing a railgun, but not mentioned so far: the linear current density per rail width should not exceed 50 kA/mm [6]. The bottom graph of Fig. 5 shows the dynamics of the projectile including the exit time. First of all it can be concluded that the combination RAFIRA+10 MJ would be able to solve the task. Therefore, the same holds for all other tasks discussed above, as they require less power. Secondly, the different mechanisms limiting the fire rate are visible: while the projectile exits at 2.53 ms, the current amplitude is still about 400 kA.

After this single shot check, the focus turns on multishot operation. The primary energy used for this experiment is about 3 MJ. That allows immediately to conclude that the number of shots is practically limited to three. Table IV summarizes the results for three scenarios. Note that the fire rates were calculated using the exit time of the projectile (see inductive energy storage in section V.).

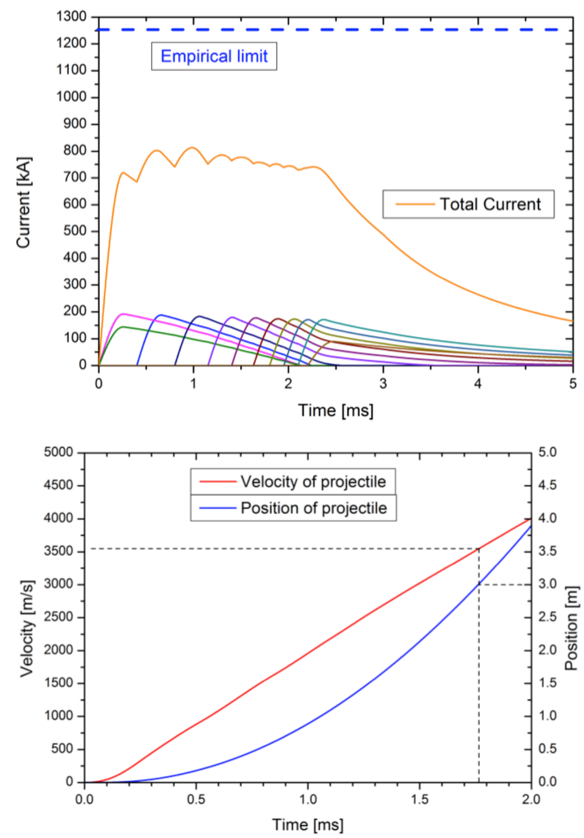

Fig. 6. Advantages of a augmenting field in single shot mode (see text).

While the obtained fire rates are well in the range of the required values, the number of shots has to be discussed. As mentioned above the heating of the rails is the most important issue in that context. In a former publication about RAFIRA [2] it was shown that using considerably less primary energy than for all cases of Table III the rail heating gets important after about 10 shots. Therefore, some counter measures have to be taken to arrive at the number of shots given in Table II. While cooling of the rails is a mandatory task and some works have been published on this topic [7, 8], here, another means to reduce heating is considered. In fact, taking into account Joule heating is already important for single shot operation, but in that case the armature is the critical component. One solution to decrease the heat load without reducing acceleration is to increase the magnetic field between the rails by external sources. This type of launcher is called augmented railgun. It is not the purpose of this paper to discuss details of such a setup, the reader is referred to existing literature [9, 10]. In order to illustrate the advantage of augmentation in single shot mode, Fig. 6 shows two cases to be compared with Fig. 5. On the upper graph, v = 2400 m/s was obtained assuming an augmenting field of 10 T. As can be seen, one would remain clearly below the empirical current limit. On the bottom graph of Fig. 6, the consequence of adding an augmented field to the configuration of Fig. 5 is shown. The velocity is remarkably increased.

TABLE IV

SINGLE SHOT CHARACTERISTICS FROM PSPICE SIMULATIONS FOR THREE SCENARIOS

Scenario	Single shot characteristics			
	Stored energy (MJ)	*Muzzle velocity (m/s)*	*t_{out} (ms)*	*Potential fire rate (Hz)*
1	0.78	1221	3.58	290
2	1.77	1788	3.34	300
3	3.05	2372	2.53	395

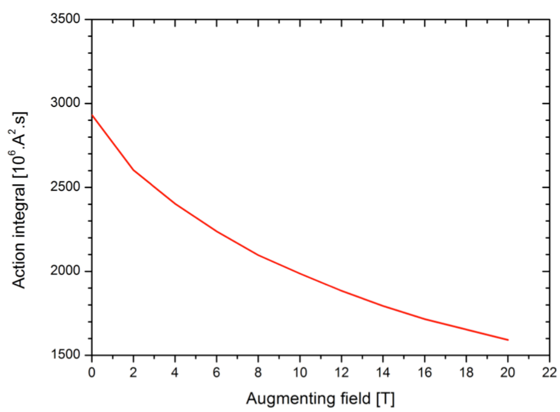

Fig. 7. Advantages of an augmenting field in multishot mode.

In order to investigate the advantages of augmentation for multishot purposes it is assumed in the following that an augmenting field exists between the rails and the question to be answered is: what can be gained in terms of number of shots due to reduced Joule heating of the rails. In a first approximation the temperature increase of the rails ΔT is proportional to the applied energy, which itself can be determined using the action integral (the term on the right hand side of (3)).

$$\Delta T \propto \int I^2 \, dt \tag{3}$$

The results obtained by PSPICE allow to calculate the action integral applied to the rails and Fig. 7 shows the relation of the augmenting field amplitude and the action integral for the case v = 1800 m/s. It can be concluded that a field of 20 T would allow to roughly doubling the number of shots. As it became clear from the calculations presented in II. C., the performance of a missile defence system is quite sensitive to the number of shots and therefore augmentation is definitively an option for this application.

V. PULSED POWER FOR AUGMENTED MULTISHOT RAILGUNS

Having shown above that augmentation is a quite promising option for missile defence systems based on railgun technology, some aspects concerning the pulsed power supply are to be mentioned. Firstly, it should be noted the following arguments are of interest for parallel augmented railguns only. Parallel augmentation means that the electric circuits of rails and augmentation are separated. Then, the requirements for both power supplies differ. While the rail circuit has to deliver current pulses as shown above, the parallel circuit can in principal be driven by a dc source. The use of permanent magnets is only an option for low power systems (saturation) and is not an option for the application considered here. Quite interesting suggestions including the use of pulsed coils were made and are to be investigated experimentally [10, 11]. Recently, an approach using superconducting coils has been proposed [12].

Even if the augmentation circuit is in parallel, a coupling via the electromotive force has to be taken into account. The back emf due to the augmenting field has to be delivered by the power supply which feeds the rails. This is of particular importance, if high ratios between the external and internal field are considered.

Finally, a power supply for missile defence should be able to reach very high fire rates. As mentioned above, the fire rate can be reduced by magnetic energy which rests in the circuit after the projectile exits. Here, the use of an inductive storage power supply is an option because it allows to cut off the current very quickly [13].

VI. CONCLUSION

ISL's RAFIRA fulfils the requirements for the most important scenarios discussed here in single shot mode. While the fire rate seems feasible as well, the number of shots required is far from today's possibilities. One way to increase this number is to use an augmented railgun and it could be shown that under the assumptions made here, field amplitudes of 20 T would allow to double the number of shots.

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