

Ballistic characterization of nanocomposite materials by means of “Coil Gun” electromagnetic accelerator

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Abstract – In this paper the authors present their activity in the field of electromagnetic machine applications for aerospace solutions. A three stage electromagnetic accelerator is under construction to perform ballistic characterization of carbon-based nanocomposite materials for anti-debris application. Preliminary experiments as well as numerical simulation have been performed with promising results in terms of bullet’s energy. Further implementation are needed in order to come closer the velocity of typical space debris (8km/s).

Index Terms—Carbon nanoparticles, Coil gun, Composite material, Space debris.

I. INTRODUCTION

IN the last decade with the advent of nanotechnology, nanocomposite materials have been acquiring importance due to the possibility of increasing the material mechanical performances while contemporary decreasing both mass and volume of the structures. Mass lowering is a “must” especially in military and space applications, since aircraft aerodynamic profile needs to be optimized and because of the high costs of launch and launcher and payload mass constraints.

The need to face up to the well know problem about “space debris” has lead many aerospace researchers to look for advanced lightweight materials for ballistic applications. Among all innovative materials, our research focus on the polymeric composite materials with inclusions of carbon nanostructures. The nanocomposites are manufactured by mixing the nanoparticles directly within the epoxy matrix in such a way to obtain a material as homogeneous as possible, in order to have a final composite with improved mechanical characteristic. Ballistic characterization is performed by means of in-house built 3-stage Electromagnetic accelerator.

II. THE COIL GUN

Electromagnetic Accelerator (EA), also called Coil Gun, is shown in fig.1: the main parts of the EA are:

- coil inductors
- tube for the projectile
- capacitors
- switch system
- diodes

Each coil inductor increase the acceleration of the projectile during its passage across itself. In fig.2 the basic scheme of the accelerator is shown. The three coil inductors can’t be of the same dimensions and turns number; in fact, since the greater is the inductor turns number the higher is the inductance, then the electric discharge impulse rise and above all decay time could result too much higher compared to the velocity of the projectile within the inductors. In such a case the efficiency of the EA could be compromised.

The greatest efficiency is obtained when the impulse is shorter than the time took by the projectile to cross the half coil inductors length. If this condition is not satisfied then the inductors will apply an attractive force on the projectile. This force will act in the opposite direction with respect to the projectile motion, thus decreasing the projectile acceleration. The diodes connected to the coil in the opposite polarity with respect to the capacitors are necessary to dump the negative voltage semi-wave oscillation caused by the capacitors discharge and inductors charge process.

The dimensioning of the inductors and the capacitors must be computed in order to obtain the maximum efficiency. This means that the coil inductors should have the lowest time charge constant while the capacitors the fast discharge time constant. This is the fundamental condition required in order to avoid the forward-back projectile magnetic strength effect. In fact, once the projectile has overcome the half coil length, the back magnetic action strength start to act on the projectile decreasing the initial forward acceleration imparted to the projectile. Since the capacitance discharge act across the coil inductors, the best compromise can be found taking to account contemporary both: the capacitance discharge constant

time and the inductors charge constant time. For the second and third coil inductors, since a higher initial projectile velocity is already acquired, the impulse time rise and decay needs to be shorter than for the first one. Such a compromise can be obtained by reducing the coil inductor turns' number, as well as the capacitors' capacitance.

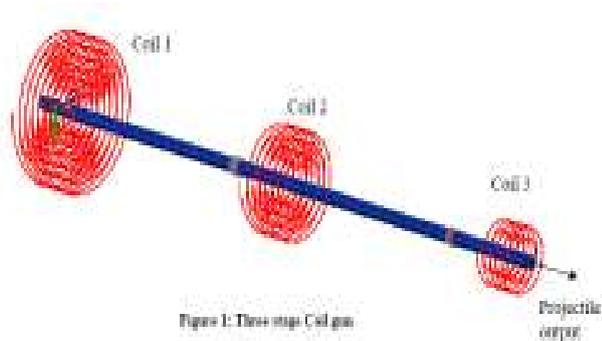


Figure 1: Three-stage Coil gun

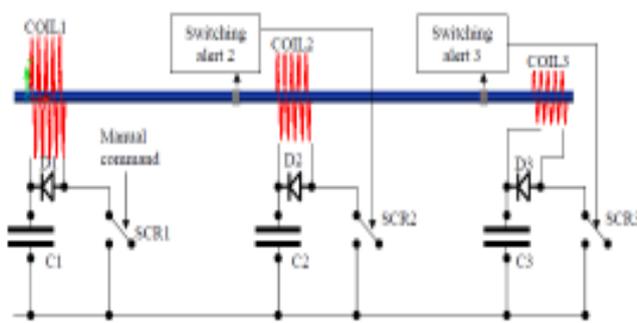


Figure 2: EA basic scheme

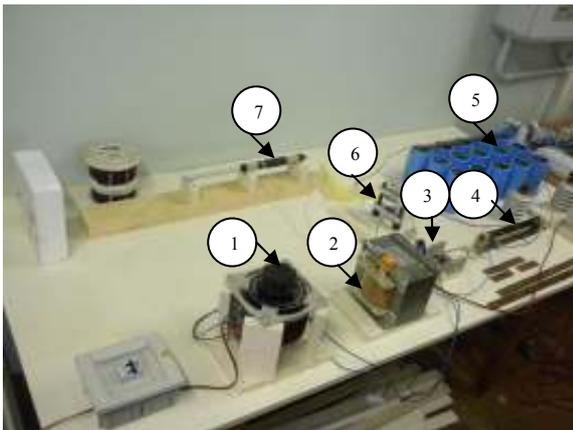


Figure 3: Picture of Coil Gun realization

Numerical simulations have indicated that by a suitable arrangement of high capacitance ($4 \times 10^3 \mu\text{F}$) capacitors as discharge trigger for a typical bullet/barrel system (mass projectile $\sim 10\text{g}$, gun length $\sim 40\text{cm}$), it's possible to reach values of $1 \div 2\text{km/s}$ for the bullet's speed, thanks to an effective coil

propulsion force of by about 10^3kN . By now the highest measured speed was near below 40m/s with the first stage only and capacitors of $0,5 \times 10^3 \mu\text{F}$; next implementation will surely give the opportunity to come nearer the computed values. In such a case our device will be really appropriate for ballistic aerospace testing, by providing faithful results about the interaction between materials and space debris ($\sim 8\text{km/s}$).

In Figure 3, a picture of first coilgun stage are reported, and in Figure 4, one capacitors if the capacitor banks are shown.



Figure 4: Picture of Coil Gun realization

In Figure 3 it is possible to notice the components of coilgun:

1. Resistive Variac ($V_{\text{input}} 220\text{ V}$, $V_{\text{output}} 0-250\text{ V CA}$);
2. Transformer ($V_{\text{input}} 250\text{ V}$, $V_{\text{output}} 1200\text{ V CA, 1A}$);
3. Rectifier Diodes to convert CA in DC supply;
4. $1\text{ k}\Omega 50\text{ W}$ resistor;
5. Capacitors, $12000\text{ MicroFarad } 200\text{ V DC}$;

6. High power SCR (3000 V max, 300 A).

7. First coilgun stage inductance.

We are currently working on simulation of inductance and capacitance to be adopted. Below the equation adapted to dimension the inductance and capacitance are reported.

The multilayer Air Core Inductance formula is:

$$L(\mu H) = \frac{31.6 \times N^2 \times r_1^2}{6 \times r_1 + 9 \times l + 10 \times (r_2 - r_1)} \quad (1)$$

Where:

L= Inductance in microHenries;

N²=Total Number of turns on coil Squared

r₁=Radius of the inside of the coil (meters)

r₂=Radius of the outside of the coil (meters)

l=Lengh of the coil (meters)

it follows that:

$$B = \mu_0 \frac{NI}{l} \Rightarrow N = \frac{Bl}{\mu_0 I} \quad (2)$$

$l = \text{Coil_length(m)} \quad I = \text{Current (A)}$

Once the values of capacitance (Farad), ddP(Volt), inductance, are fixed as a constraint due to the available hardware then equalling the energy stored in the capacitors to that gained by the inductors and assuming that all the energy of capacitors are transferred to inductance during the discharge phase, then it is possible to determine the instantaneous current across the inductor:

$$E(J) = \frac{1}{2} LI^2 = \frac{1}{2} CV^2 \Rightarrow I_{\max} = \sqrt{\frac{CV^2}{L}} \quad (3)$$

In order to compute the discharge current on capacitors we can adopt the following equation

$$I_c = I_{\max} \left(e^{\frac{t}{RC}} \right) \quad (4)$$

In order to compute the charge current on inductance we can adopt the following equation

$$I_L = I_{\max} \left(1 - e^{\frac{t}{L/R}} \right) \quad (5)$$

In order to compute the theoretical propulsion force on the projectile due to the current on the inductance we can first determine the total amount of current across the inductance combining Equation (4) and (5), and then on inductance we can adopt the Equation (6)

$$I_{C-L} = I_{\max} \left(e^{\frac{t}{RC}} \right) \left(1 - e^{\frac{t}{L/R}} \right) \quad (6)$$

$$\text{Propulsion_Force} = \frac{\mu_0 N^2 2\pi a^2}{2l^2} I_{C-L}^2 (\mu_r - 1) \quad (7)$$

In order to compute the effective force on projectile taking into account its ballistic coefficient we can use the equation below relating the air friction forces to the projectile velocity and projectile geometrical properties:

$$F_{\text{atm}} = ma_{\text{atm}} = \frac{1}{2} c_D S \rho v^2 \quad (8)$$

Where:

S = directly exposed projectile surface to the air friction;

C_D = projectile ballistic coefficient

ρ = air density (1,225 kg/m³)

The input and output data for the coil inductance are

Input:

Input_data	
N°spire=	150
coil Length(m)=	0.07
Radius of the inside of the coil (m)=	0.007
Radius of the outside of the coil (m)=	0.06
K(short solenoid)=	1
Wire Gauge(AWG)=	0
Metal Resistivity(Ohm*m)=	0.0000001
Estimated Total Loss resistance	0.005

Meaning of colour	User Input data
	Equation results

Output:

Output_data	
B (Tesa)=	4.03E+01
L(Henry)=	2.90E-05
Wire Diameter(mm)=	8.25E+00
Approx_Wire_Length(m)=	3.16E+01
Approx_(Wire+Loss)_Resistance(Ohm)=	1.87E+00
Approx_Inductance_Time_Constant(s)=	1.55E-05
Approx_Inductance_Time_Charge(s)=	9.30E-05
Stored_Inductance_energy(J)=	3.25E+03
I_max(A)=	1.50E+04
WireCoil_Resistance(Ohm)=	5.90E-02
Max_Joule_Loss_Power_on_Inductance(W)=	1.32E+07
Max_Joule_Loss_Energy_on_Inductance(J)=	1.13E+06

The input and output data for the capacitors are:

Input:

Input_data	
Average Charge Voltage(V)=	1000
Capacitance(Micro Farad)=	6500
Capacitance+Inductors time constant(s)=	1.21E-02
Approx_Capacitance_Time_Discharge(s)=	8.50E-02

Output:

Output_data	
Capacitance_Stored_Energy(J)=	3250

The input and output data for the coilgun are:

Input:

Input_data	
Projectile relative material permeability Mur=	1000
Projectile mass(kg)=	0.01
Projectile radius(m)=	0.00038
Projectile Ballistic coefficient=	1
Air density(kg/m^3)=	1.225

Output:

Output_data	
Peak_Coil_Current(A)=	1.50E+04
Peak_Propulsion_force(N)=	9.95E+07
Peak_Projectile_acceleration(m/s^2)=	9.95E+09
Time_elapsed_after_onehalf_lenght_of_coil_crossed(s)=	2.65237E-06

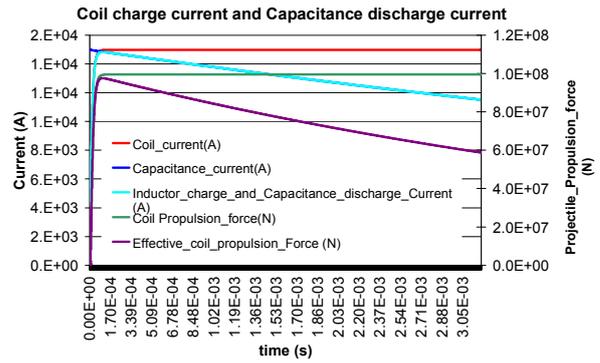


Figure 5: Coilgun current using 150 turns inductance

From simulation in Figure 5, it is possible to observe that the decay of the current in the coil inductance is quite slow. Reducing the inductance turns number to 50 the current decay is faster and such behaviour assure that the projectile are not subject to a retracting force after it crossed the half inductance length $L/2$. this is particularly important in the second and third stage of the coilgun.

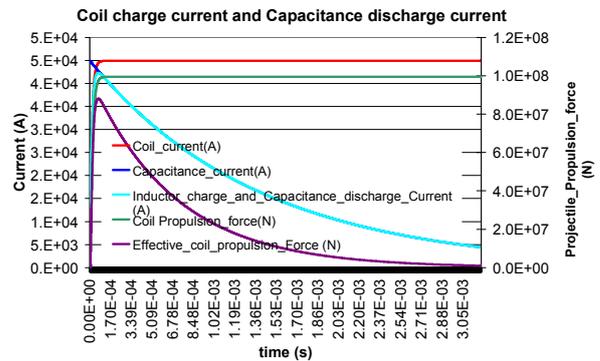


Figure 6: Coilgun current using 50 turns inductance

III. EXPERIMENTAL RESULTS

In this section the preliminary results collected from the first shots fired off are briefly presented. By now the coil gun only is under consideration: ballistic characterization of nanocomposites will be soon provided after a complete optimization, in terms of both bullet's speed maximization and measurements reproducibility. Tab.1 here below summarizes the results obtained for two steel bullets (S, L) two copper coils (A, B) and three different capacitors arrays (C1, C2, C3) at several input voltages.

BULLET SPEED (m/s)												
d.d.p. (Volts)	COIL A						COIL B					
	C1		C2		C3		C1		C2		C3	
	S	L	S	L	S	L	S	L	S	L	S	L
350					22							
400					24	18					37	
460					24.5	18						
500				< 17	25	19					43	
550					25	23						
600	< 17		28.5	< 17	24	25					49	52
660					23.5	28						
700	18		31		23	30					55	62
750					22	30.5						
800	21	< 17	31.5	25	20	32					58	74
850	24				19	33						
900	26		32			34					59	
950	29					34						
1005	31		31			34						
1050					< 17	33						
1095	34		29									

Tab.1. Coil Gun: measurements of speed (*ProChrono* chronograph, minimum speed 17m/s, precision 0.5m/s).

System parameters:

- Aluminium barrel: length 31.6cm, outer diameter 10mm, inner diameter 7.6mm.
- Steel bullets: S) length 8cm, diameter 6.3mm, mass 17.2g; L) length 16cm, diameter 6.3mm, mass 36.6g.
- Coils: A) wire diameter 2.1mm, length 15cm, n° coils 58, n° turns 8; B) wire diameter 3.2mm, length 14cm, n° coils 40, n° turns 7.
- Capacitance: 12000 μ F capacitors C in three arrangements
C1 : five C in series, equivalent capacitance 2400 μ F;
C2 : two C1 in parallel, equivalent capacitance 4800 μ F;
C3 : three C1 in parallel, equivalent capacitance 7200 μ F.

Fig.7 shows a graphic comparison of the most significant results obtained so far. A first preliminary analysis of the experimental results listed in Tab.1 and outlined in Fig.7 stresses an intriguing and not obvious dependence between the several variables involved, mainly between the time charge/discharge circuit response and the mass of the bullet. It's clear, for example, that for coil A and bullet S the system efficiency raise up by decreasing the total capacitance, thus supplying less energy to the system (see eq.3).

That is of course connected to the lower time employed by the smaller bullet to reach the coil center, over which it's recalled back, as explained above. To get the highest efficiency all the parameters have to be accurately matched: the results obtained for coil B and bullet L suggest that a suitable arrangement of capacitors bank may let us able to raise the bullet speed up to 100m/s with the only first stage of the coil gun. Further improvements will be soon reported.

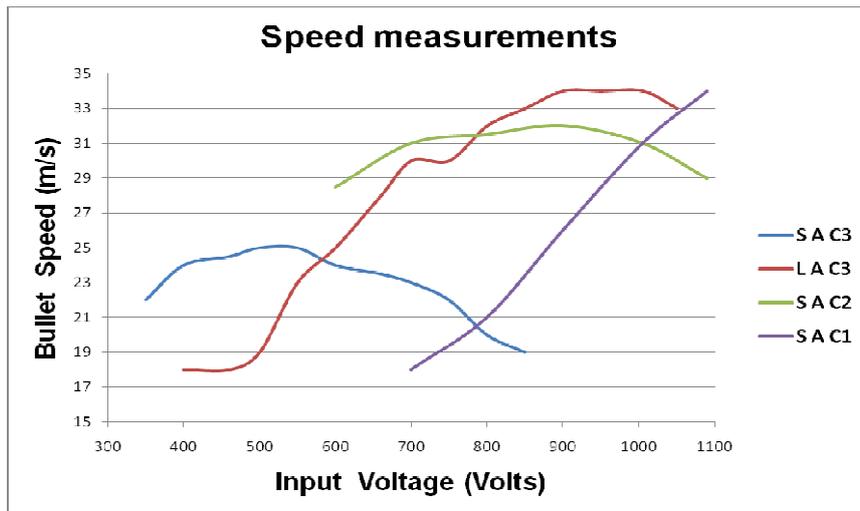


Fig.7. Comparison of speed measurements for different Coil Gun arrangements.