On the Design of Coilguns for Super-Velocity Launchers

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This paper deals with the design of a super-velocity launcher with muzzle velocity up to 8 km/s. It addresses the design specifications of the linear induction section of the launcher having a 4-km/s breech velocity, and utilizing a projectile weighing 1 kg. The overall launcher is a hybrid design, using a gas gun to obtain the initial 4-km/s speed at the input to the coil launcher. The design sequence starts with the maximum temperature allowed by the sleeve material; continues by selecting the required number of sections in the barrel; the dimensions of the drive coils are determined; and our existing computer code is used to optimize the transition between the gas gun and the first section of the coil gun, and between successive sections of the barrel. The code utilizes our latest design scheme; that is, the drive coils are connected in parallel; one flywheel generator per pole is used; and all of the generators in a given section are shaft-coupled, so that they all rotate at the same speed. The design specifications are presented in this paper together with simulation results for the phase voltages, the currents, and the acceleration forces.

***Index Terms*—Electromagnetic launchers, hypervelocity launchers, induction coil launchers.**

I. Introduction

THIS PAPER deals with the design of a super-velocity launcher with muzzle velocity up to 8 km/s. The first section is a gas gun, which accelerates the projectile to 4 km/s. This is the input velocity to the second section, a linear induction coil launcher. In our previous work, muzzle velocities up to only 2 km/s were studied [1]. Flywheel motor/generator sets are used to power the linear induction section of the launcher.

The barrel of the linear induction launcher (LIL) consists of a long, coaxial, sectionalized array of coils, energized in polyphase fashion. It serves to accelerate the projectile, the payload of which is enclosed within a cylindrical conducting sleeve. Each section of the barrel array is fed at a constant frequency, but each succeeding section, traversed by the projectile at higher and higher velocity, is energized at an increasingly higher frequency [2].

The flywheel motor/generator set arrangement is such that each pole-pair along the barrel requires a set of two shaft-coupled generators; that is, one generator per pole (Fig. 1). In this case, 10 drive coils are used to make one pole-pair. The left-side five-phase generator feeds five drive coils, supplying the positive (N) pole; the right-side generator supplies the negative (S) part of the pole-pair. This configuration, equivalent to a parallel connection of the drive coils (1&6, 2&7, etc.), leads to a substantial reduction in input voltage levels, and to more efficient energy utilization [3].

The two most critical issues in the design of the coil launcher are the electrical stresses on the drive coils in the higher velocity sections and the heat generated in the conductive sleeve portion of the projectile. The following sections discuss the preliminary design procedure, present the results of a quasi-steady-state calculation, and give final simulation results for the phase voltages, the currents, and the acceleration forces.

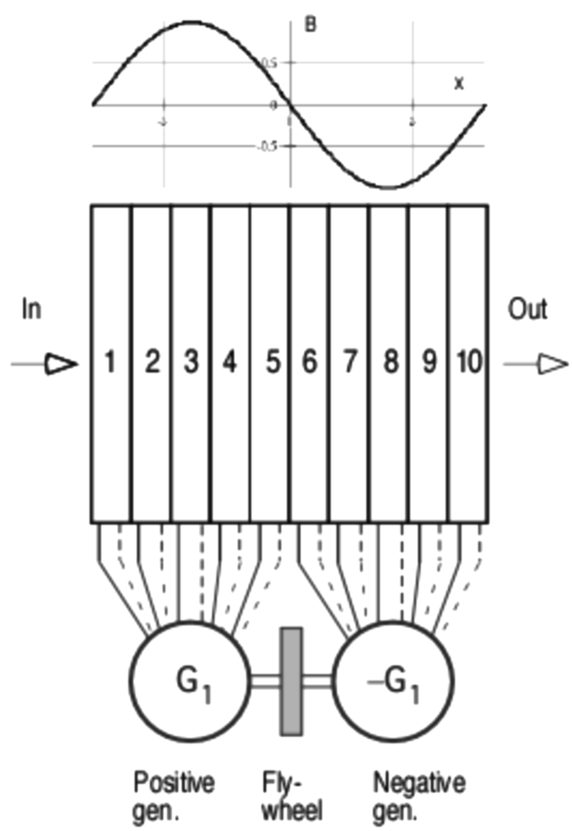

Fig. 1. Two-poles, 10 drive-coils, fed by a set of two shaft-coupled generators.

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II. Design Procedure

The LIL design is based on a quasi-steady-state preliminary procedure [4], where the most critical specification is the maximum temperature of the sleeve material. Clearly, a transient analysis [2] is required to validate and modify that preliminary design.

The following is the procedure used to carry out the quasi-steady-state preliminary design.

Step 1) The speed gain ΔV_n in the final section of an n-section launcher is first assumed to be

$$\Delta V_n \cong \frac{V_{\text{out}} - V_{\text{in}}}{n} \tag{1}$$

where V_{out} is the muzzle velocity and V_{in} is the breech velocity.

Step 2) The synchronous speed $V_{S(n)}$ of section n is

$$V_{S(n)} = \frac{V_{\text{out}}(n)}{1 - S_o} \tag{2}$$

where S_o is the exit slip of the section (it is the same in all sections).

Step 3) The power supply frequency f_n needed for the section is

$$f_n = \frac{V_{S(n)}}{2\tau} \tag{3}$$

where τ is the pole-pitch (length of one pole).

Step 4) The input velocity $V_{\text{in}(n)}$ of section n (equal to the output velocity $V_{o(n-1)}$ of the preceding section) is

$$V_{\text{in}(n)} = V_{\text{out}} - \Delta V_n. \tag{4}$$

Step 5) The input slip $S_{i(n)}$ of the section is

$$S_{i(n)} = \frac{V_{S(n)} - V_{\text{in}(n)}}{V_{S(n)}}. \tag{5}$$

Step 6) The critical slip $S_{C(n)}$ of section n is

$$S_{C(n)} = \sqrt{\frac{S_{i(n)}^2 - S_o^2}{2 \cdot \ln \frac{S_{i(n)}}{S_0}}}. \tag{6}$$

Step 7) Check—The critical slip $S_{C(n)}$ [5] must also relate to the frequency f_n (3)

$$S_{C(n)} = \frac{1}{d \cdot \gamma \cdot \mu_0 \cdot V_{S(n)}} \tag{7}$$

where d is the thickness of the sleeve, γ is the electrical conductivity of the sleeve material, and μ_0 is the permeability of air.

If there is no match between Step 6) and 7), ΔV_n must be modified. Thus, the design begins at the last section, where the muzzle velocity is specified, and continues back down to the first section by repeating the series of Steps 1)–7). If the correct breech velocity (also specified) is not obtained, then the whole iteration procedure has to be restarted with a different S_o.

Step 8) The mass M_S of the sleeve is

$$M_S = \pi \cdot d(D - d)L_S \cdot \delta \tag{8}$$

where D is the outer diameter of the sleeve, δ is the density of the sleeve material, and $L_S = 2\tau$ is the sleeve length.

Step 9) The transit time t_n in section n is a function of the average acceleration a_m (also specified) of the projectile in the barrel

$$t_n = \frac{V_{\text{in}(n)} - V_{o(n)}}{a_m}. \tag{9}$$

Step 10) The length l_n of section n is

$$l_n = \frac{V_{\text{in}(n)} + V_{o(n)}}{2} t_n. \tag{10}$$

Step 11) The gain in kinetic energy $W_{k(n)}$ of the projectile (i.e., sleeve + payload of mass M_L) is

$$W_{k(n)} = (M_S + M_L)\frac{V_{o(n)}^2 - V_{\text{in}(n)}^2}{2}. \tag{11}$$

Step 12) The energy W_n required for barrel-section n to obtain the previous kinetic energy is

$$W_n = \frac{W_{k(n)}}{1 - S_{\text{avg}(n)}} \tag{12}$$

where $S_{\text{avg}(n)} = (S_{in(n)} + S_o/2)$ is the average slip in section n.

Step 13) The ohmic loss ΔW_n in the sleeve material during its transit of section n is

$$\Delta W_n = W_n \cdot S_{\text{avg}(n)}. \tag{13}$$

Step 14) The temperature rise θ_S developed in the sleeve is

$$\theta_S = \frac{1}{c \cdot M_S} \sum_{i=1}^{n} \Delta W_i \tag{14}$$

where c is the specific heat of the sleeve material.

If the temperature θ_S is too close to the melting point of the sleeve material, the number of sections n needs to be increased.

III. 8-km/s Launcher—Design Specifications

The previous quasi-steady-state procedure was used to design a linear induction launcher for a muzzle velocity of $V_{\text{out}} =$ 8 km/s. It was assumed that a gas gun provides a breech velocity of $V_{\text{in}} = 4$ km/s.

Design specifications were chosen to be as follows. An aluminum projectile $(M_L = 0)$ of $L_S = 20$ cm having an outer diameter of $D = 7$ cm, and a thickness of $d = 1$ cm. (Al has a melting point of 659 °C [6]). It has a mass of $M_S = 1.02$ kg. The projectile length sets the pole-pitch at $\tau = 10$ cm. Assume an exit slip of $S_o = 0.005$, a total number of sections $n = 20$, and an acceleration of $a_m = 80$ kG. The results are shown in Table I.

To allow 10 drive coils per pole-pair (as shown in Fig. 1) at a pole-pitch of $\tau = 10$ cm, each coil has to have a width of

TABLE I
QUASI-STEADY-STATE RESULTS FOR THE DESIGN OF THE 8-KM/S LAUNCHER

Sec No	Freq. kHz	Vout m/sec	Length m	Time msec	Energy MJoule	Temp. °C
1	21.3	4234	1.46	0.355	0.964	35.2
2	22.4	4464	1.50	0.345	0.999	69.4
3	23.6	4689	1.54	0.336	1.032	102.7
4	24.7	4911	1.57	0.328	1.062	135.3
5	25.8	5128	1.61	0.320	1.091	167.0
6	26.8	5342	1.64	0.313	1.119	198.1
7	27.9	5552	1.67	0.306	1.144	228.4
8	28.9	5758	1.69	0.299	1.168	258.0
9	30.0	5962	1.72	0.293	1.191	287.1
10	31.0	6162	1.74	0.287	1.212	315.5
11	32.0	6358	1.76	0.281	1.232	343.3
12	32.9	6552	1.78	0.275	1.250	370.6
13	33.9	6743	1.79	0.270	1.268	397.4
14	34.8	6930	1.81	0.265	1.284	423.6
15	35.8	7115	1.82	0.260	1.299	449.4
16	36.7	7298	1.84	0.255	1.313	474.7
17	37.6	7477	1.85	0.250	1.326	499.5
18	38.5	7654	1.86	0.246	1.338	523.8
19	39.3	7828	1.87	0.241	1.349	547.8
20	40.2	8000	1.88	0.237	1.360	571.3
	Total	8000	34.38	5.76	24.00	571.3

TABLE II
SIMULATION RESULTS FOR A 20-SECTION LINEAR INDUCTION LAUNCHER HAVING A 5-ϕ FLYWHEEL-GENERATOR PER POLE-PITCH

Sec. No.	Phase kV	Curr. kA	Length m	# of gen.	Vout m/sec	Temp. °C
1	16.0	40.0	1.5	15	4294	36.7
2	16.5	39.5	1.5	15	4540	71.1
3	17.0	39.0	1.5	15	4765	101.8
4	17.5	38.0	1.6	16	4961	132.9
5	18.0	37.5	1.6	16	5183	162.6
6	18.5	37.0	1.6	16	5409	194.7
7	19.0	36.5	1.7	17	5580	223.8
8	19.5	36.0	1.7	17	5788	252.1
9	20.0	36.0	1.7	17	5984	282.4
10	20.5	36.0	1.7	17	6170	308.6
11	21.0	35.0	1.8	18	6387	338.3
12	21.5	35.0	1.8	18	6578	364.3
13	22.0	35.0	1.8	18	6754	389.8
14	22.5	35.0	1.8	18	6909	417.2
15	23.0	35.0	1.8	18	7096	441.1
16	23.5	35.0	1.8	18	7323	467.0
17	24.0	35.0	1.9	19	7525	491.4
18	24.5	35.0	1.9	19	7619	514.9
19	25.0	34.0	1.9	19	7815	540.4
20	25.5	34.0	1.9	19	8011	562.8
		Total	34.5	345	8011	562.8

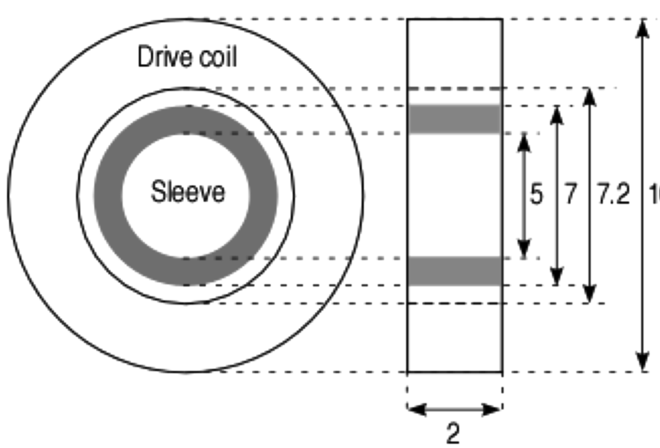

Fig. 2. Dimensions (in centimeters) of drive-coil and sleeve.

2 cm (including insulation). The dimensions of each drive coil are given below (Fig. 2). Clearly, the calculated length of each section in Table I must be slightly adjusted to make room for the actual 2-cm drive coils (see Table II). Each (pancake) coil was assumed to have four turns. The airgap between barrel and sleeve is 1 mm. In this paper, the projectile itself consists only of its aluminum sleeve.

IV. SIMULATION RESULTS

The previous specifications were fed into our computer code [3]. The results are shown in Table II, where:

- Phase kV: peak phase voltage per section;
- Curr. kA: average peak phase current; calculated as the arithmetic average of the peak currents in the parallel-connected branches;
- Length m: the actual length of each section;
- # of gen.: number of flywheel generators in a section; one generator per pole-pitch (5 drive coils);
- V_{out} m/s: exit speed of each section;
- Temp. ° C: max temperature of the sleeve in a section.

Note: In the computer simulation, the frequencies were kept to the values given in Table I.

At the breech, the projectile enters the magnetic traveling wave of the first section at 4-km/s velocity. As a result of the buildup of induced azimuthal currents in the sleeve, a strong deceleration force may be introduced. Therefore, to induce the required azimuthal currents prior to entering the launcher, a booster section was placed just before the first section. It has the same length as the sleeve, 20 cm, and has 10 coils that are fed by 5-ϕ voltages at a frequency identical to that of the first section.

Waveforms of the five phase currents in generator #9 energizing coils 41–45 of the 20th section of the barrel are shown in Fig. 3. The section length is 1.9 m, at 19 pole-pitches, and it is fed by a set of 19 shaft-coupled generators. All 19 generators feed the section simultaneously. When the projectile passes under coils 41–45 (fed by generator #9), the phase currents increase dramatically because the equivalent inductance of those coils decreases [7].

The accelerating force curve is presented in Fig. 4(a), and the corresponding velocity curve in Fig. 4(b).

The force fluctuation [Fig. 4(a)] leaves room for improvement. That can be achieved by optimizing the initial position of the projectile in a section. Initial position means the distance between of the rear end of the sleeve and the rear end of the section it is about to enter. It can also be improved by adjusting the

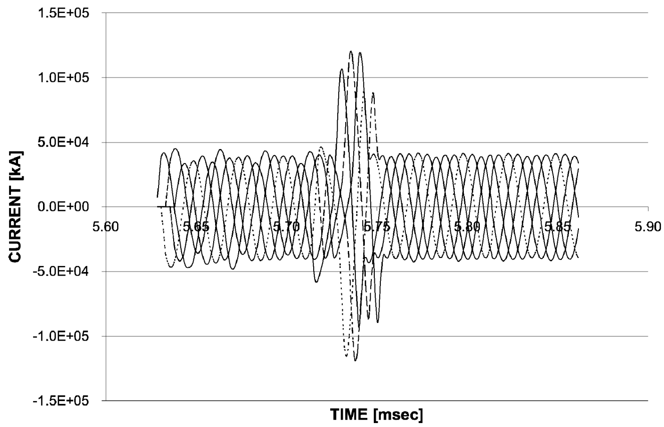

Fig. 3. 5-ϕ currents in generators #9 in section 20 of the launcher. Current is shown to increase as the projectile passes through coils 41– 45.

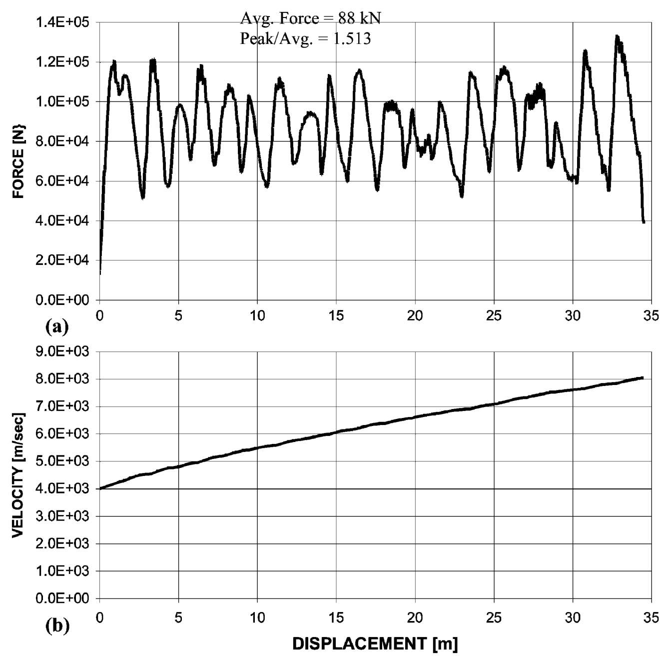

Fig. 4. (a) Accelerating force and (b) velocity versus displacement along the barrel.

initial phase-angle of the phase voltages in each section of the launcher.

V. Conclusion

This paper has discussed the procedure for a quasi-steady-state preliminary design of a linear induction launcher. It addressed the specific requirements of a super-velocity launcher, where the initial 4 km/s is provided by a gas gun, and the muzzle velocity of 8 km/s is achieved by the coil launcher. The preliminary design results were then analyzed by a transient computer simulation code, and modifications were made when necessary. The results of both procedures are presented in this paper. The resultant phase voltages were kept below 30 kV/cm of coil length, the breakdown voltage of air. This suggests that the linear induction launcher can be used for super-velocity applications.

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