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Study of the Feeding Mode Effect on the Linear Induction Launcher (LIL) Performances

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Abstract: - Considering the transitory character of its operation, the linear induction launcher has dynamic performances such as the propulsion force and the projectile velocity which are significantly dependent not only on its geometrical dimensions but also on its feeding. In this paper, the effect of the latter, which is undoubtedly of capital importance, on the performances of the device is studied thanks to a model obtained by an analytical method called the coupled circuits method which we implemented. Our study related to two different prototypes. The first is a low speed laboratory prototype which comprises only one section of inductive reels and which was used to us as practical model on which tests were carried out for the validation of the adopted method. Let us note that the results obtained with these tests are given in this present paper. As for the second prototype, of which the geometrical data are fixed by holding account of the study undertaken on the first prototype, it comprises two sections of inductive reels. It is used as model of simulation in order to meter in obviousness the influence of the mode of feeding on the dynamic behavior of the projectile during its evolution within the sections of the launcher and at the time of its transition from the first section to the second section.

Key words: Electromagnetic propulsion, Linear induction launchers, Induction launchers power supply, Coupled circuits, Dynamic performances.

1 Introduction

The induction electromagnetic launchers recently received increased attention for the significant advantages that they present relative at the other types of launchers. Among these advantages, the absence of contact between the fixed part (gun) and the moving part (projectile), which allows an almost permanent re-use of the gun, and the possibility of reaching very high speeds going until a few kilometers a second. The linear induction launcher (LIL) consists of a projectile: cylindrical conducting matter tube, and a barrel made up of inductive reels supplied with an electric source of energy Fig.1. The two types of sources of energy commonly used are generators and capacitors banks.

An induction launcher supplied with generators of sinusoidal tensions is similar to classic linear induction machines. Nevertheless, the launcher differs from this last in: 1. no ferromagnetic material is used; 2. the secondary (projectile) is shorter than the barrel; 3. The time of transit of the projectile in the barrel is comparable with the time-constant of the currents in the reels and the projectile.

The induction launchers supplied with capacitors banks can be classified in two types according to the firing sequence of the switches ordering the discharge of the capacitors. The first, called the travelling wave coilgun, is similar to the launcher supplied with generators [1]. The barrel of the LIL being divided into several sections, the reels of each section are connected to form a system of three phases each one supplied with a capacitor bank [2]. The capacitance of each bank resonates with the inductance of the phase which it feeds. For the second type, known as capacitor-driven multistage coilgun, the reels of the barrel are not connected between them. Each one of them is fed by its own bank. In this case, the passage of the projectile by the middle of each reel is used to commutate the switches of the capacitors banks.

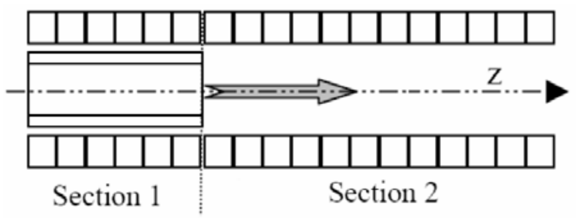

Fig.1 : Geometry of a two-sections launcher

2 Theoretical development

The coupled circuits method used is based on an equivalent circuit which can be schematized in the following way:
The massive conducting parts of the system are shared in elementary elements in which a uniform diffusion of current is supposed. Each element of volume has its electric parameters (resistance, self inductance, and the mutual inductance with the other elements) which are calculated. The electric and mechanical equations governing the behavior of the device are formulated on the basis of the equivalent circuit adopted. The whole of the equations is solved with a numerical method.

The behavior of the launcher of Fig.1 can be translated according to the electric parameters which characterize it in the form of equations which are written in matrix form as follows:

$$[V] = \{R + vG\}[I] + \{[L] + [M]\}\frac{d}{dt}[I] \qquad (1)$$

Where :
[V] and *[I]* : Column vectors, with (m+n) elements, respectively of the tensions and the currents.
[R] and [L] : Diagonal matrices with (m+n) elements, respectively of resistances and self inductances.
[M] : Square matrix with(m+n)×(m+n) elements of the mutual inductance.

$$[G] = \frac{d[M]}{dz} \; ; \; v = \frac{dz}{dt}$$

The relations used for the calculation of the elements of the matrices $[L]$ and $[M]$ are those given in the references [5], [6], [7]. It should be noted that mutual inductance between the inductive reels and the rings of the projectile are related to Z which definite the position of the projectile compared to the barrel.

From the preceding considerations, one can express the magnetic energy stored in the system as follows:

$$E = \frac{1}{2}L_sI_r^{\,2} + \frac{1}{2}L_rI_r^{\,2} + M_{sr}I_sI_r \qquad (2)$$

The force producing the displacement dz of the projectile is given by:

$$F_z = \frac{dE}{dz} = I_sI_r\frac{dM_{sr}}{dz} \qquad (3)$$

The acceleration of the projectile is obtained from (3) and is written:

$$a_z = \frac{F_z}{m} = \frac{I_sI_r}{m}.\frac{dM_{sr}}{dz} \qquad (4)$$

With m: mass of the projectile.

3 Applications and results

3.1 Prototype 1: A one-Section Linear Induction Launcher

The first prototype of axisymmetric linear induction launcher (LIL) considered in the current study have only one section with six inductor coils. The linear induction launcher is supplied by three phase voltages generators V_A, V_B and V_C with A, -C; B, -A; C, -B phases connection sequence and expressed as follow:

$V_A(t) = V_m \sin(2\pi\ f\ \mathrm{t})$

$V_B(t) = V_m \sin(2\pi\ f\ \mathrm{t} - \frac{2\pi}{3})$

$V_C(t) = V_m \sin(2\pi\ f\ \mathrm{t} - \frac{4\pi}{3})$

With : $V_m = \sqrt{2}\ 260\,V$; $f = 50\,Hz$

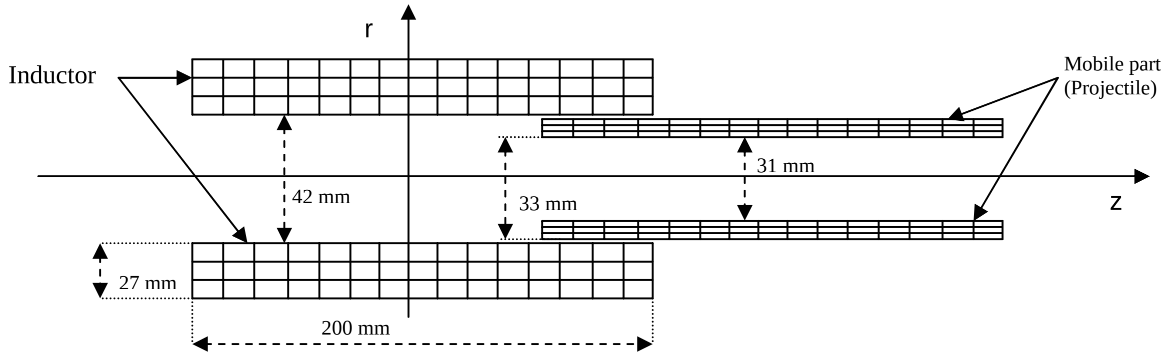

Fig.2 Domain discretization and geometrical characteristics

In Fig.2 is presented the domain discretization in the [r,z] plan which represent a section with the mobile part of the axisymmetric LIL divided into annular elementary coils. The geometrical characteristics are also considered to be the same than those given in references [2]-[5]. The mobile part is an aluminum material with electrical conductivity about $3.816\ 10^7\ s/m$ and mass equal to 98 g.

The results, experimental and of simulation, obtained with this prototype are summarized by figures 3 and 4. Those show the effect of the supply voltage and the initial position of the projectile on the muzzle velocity.

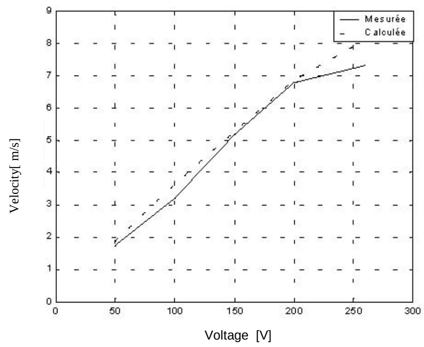

Fig.3 : Dependence of muzzle velocity on phase voltages
------ simulation —— experiment

Confrontation between the given results show that in the case of speed variation with source voltage they agree well until 220 V value. After this voltage value some difference appears which would be reduced when increasing the number of unknowns with the refine of the domain discretization.

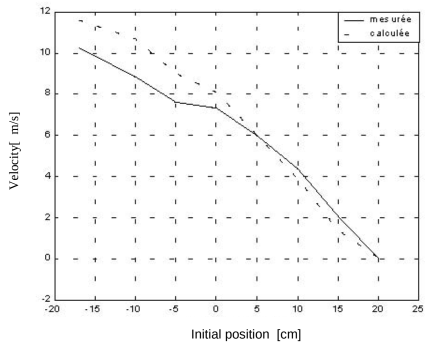

Fig.4 : Dependence of muzzle velocity on the projectile initial position
----- simulation —— experiment

3.2 Prototype 2: Two-Sections Linear Induction Launcher

In this current study an axisymmetric linear induction launcher (LIL) prototype which consist on a two-sections one with six and twelve inductor coils in the first and the second section respectively was considered. Each section of the axisymmetric linear induction launcher was feed at first by three phase generators and then by capacitor banks. Geometrical and physical characteristics of the current prototype are as follow:

First and second section:
- Inner radius : 26.75 mm
- Outer radius: 41.75 mm
- Electrical conductivity: $5.9\ 10^7\ s/m$

Projectile:
- Inner radius : 24.35 mm
- Outer radius : 25.65 mm
- Electrical conductivity: $3.816\ 10^7\ s/m$
- Mass: 100 g

3.2.1 Feeding by generators

a. Starting section

In the present case study the starting section was supplied by three phase voltages generators with the same forms that the one used in prototype 1:

$$V_{A1}(t) = V_{m1}\sin(2\pi\ f_1\ \mathrm{t} + \varphi_1)$$
$$V_{B1}(t) = V_{m1}\sin(2\pi\ f\ \mathrm{t}_1 - \tfrac{2\pi}{3} + \varphi_1)$$
$$V_{C1}(t) = V_{m1}\sin(2\pi\ f_1\ \mathrm{t} - \tfrac{4\pi}{3} + \varphi_1)$$

With : $V_{m1} = 500\,V$; $f_1 = 210\,Hz$

φ_1: Phase delay at the initial time starting section

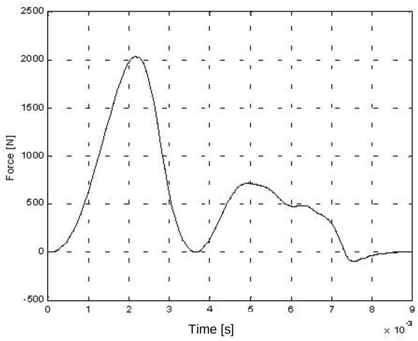

Fig.5 : The force profile in the starting section

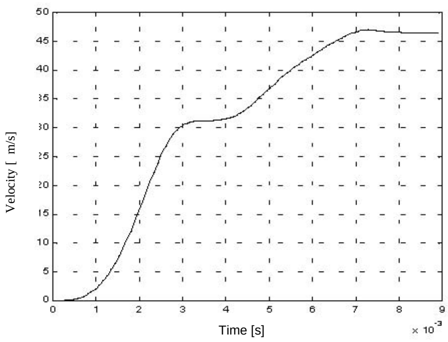

Fig.6 : Projectile velocity profile

In Fig.5 and Fig.6 are presented the acting force on the projectile and the velocity profile depending on time variation when only the first section is supplied by three phases generators. It show that the maximum value of the acting force on the projectile is about 2000 N and the output muzzle velocity of the projectile is around 47 m/s. The profile of the force and the muzzle velocity respectively are similar than the known results given in scientific literature [1].

The eddy currents waves forms obtained and given in Fig.7 are non sinusoidal. Consequently the signal would contain a constant component of current which will induces additional projectile heating.

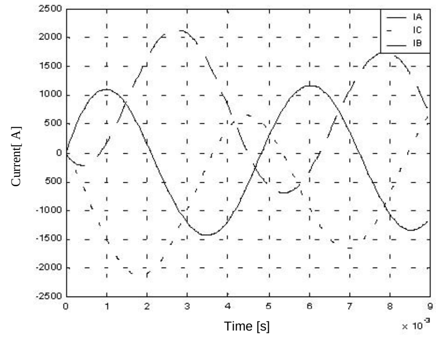

Fig.7 : Three phase currents Vm=500V, f=210Hz

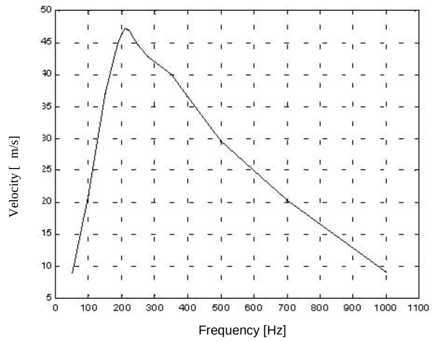

Fig.8 : Dependence of muzzle velocity on the primary currents frequency

The frequency value was chosen in the current study as an optimal value according to the results obtained and presented in Fig.8.

b. Two sections

A study of the linear induction launcher (LIL) performances when considering the first and a second section of the LIL was focalized on the influence of the projectile position, initial time of the second section supply, on the muzzle velocity. This consists on the study of the optimal time corresponding to the transition of the projectile from the first to the second section when the second section have to be supplied by generators. The three phase voltages generators feed of the LIL second section has the following form:

$$V_{A2}(t) = V_{m2}\sin(2\pi\ f_2(\mathrm{t} - \mathrm{t}_2) + \varphi_2)$$
$$V_{B2}(t) = V_{m2}\sin(2\pi\ f_2\ (\mathrm{t} - \mathrm{t}_2) - \tfrac{2\pi}{3} + \varphi_2)$$
$$V_{C2}(t) = V_{m2}\sin(2\pi\ f_2\ (\mathrm{t} - \mathrm{t}_2) - \tfrac{4\pi}{3} + \varphi_2)$$

With : $V_{m2} = 1500\,V$; $f_2 = 400\,Hz$
t_2: second section time feeding ; φ_2: commutation phase angle at time t_2.

Feeding time (ms)	4.975	6.214	7.288	8.36
Projectile position Z(cm)	10	15	20	25
Muzzle velocity (m/s)	85.2	86.5	83	75

Table 1 : Dependence of muzzle velocity on feeding time of the second section

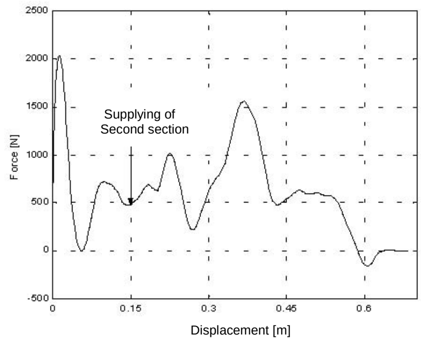

Fig.9 : The force profile in the two-section barrel Z=15cm

With the use of several feeding time to predict higher performances of the LIL, as it shown in Table.1, the optimal value of the muzzle velocity is v = 47 m/s for the position of the projectile z = 0.015 m corresponding to time t = 0.0062 s.
The difficulties encountered in the projectile transition process from the first section to the second one are the constant component of eddy currents and the phase delay of projectile eddy currents between the previous and upcoming section.

3.2.2 Feeding by capacitor banks

A capacitor banks feed of linear induction launcher was investigated considering the same prototype studied earlier (section 3.1.1) in order to establish a comparison between results. Therefore, in the present study each phase of the LIL was feed by its own capacitor bank about 500 V and 1500 V for the first and the second sections respectively. The first section has a capacitor equal to 2200 µF and the second one was 280 µF.

a. Starting section

A first section feed by capacitor bank with 60° phase delay permit to obtain a maximum value more than 1000 N (Fig.11) for the acting force on the projectile when in Fig.10 a maximum current of 1200 a could be note.

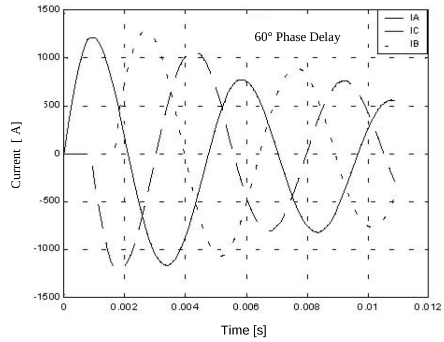

Fig.10 : Three phase currents Vc0=500V, C=2200µI

In Fig.12 the dependency of the muzzle velocity on phase shift shows that the optimal value of the muzzle velocity was obtained with a phase delay corresponding to 60°(exactly the same phase delay considered in this part).

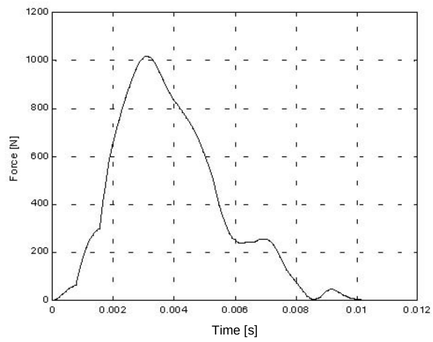

Fig.11 : Force profile

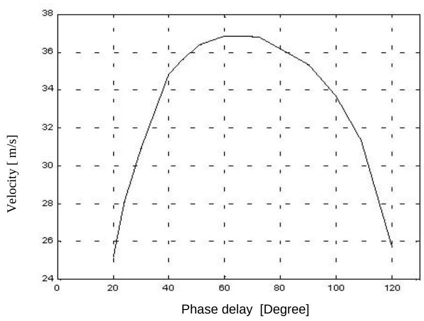

Fig.12 : Dependence of muzzle velocity on phase shift

b. Two sections

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The study of different feeding time of the second section permit to obtain the results summarized in Table.2 where the higher value of the muzzle velocity correspond to a projectile position of z = 0.02 m. A feeding time of the second section which ensure the transition from the first to the second section was more important than the one obtained in the case of generators feed. The second section feed has the consequence to increase the propulsion force and the output muzzle velocity compared to a one-section LIL as it was shown in Fig.14 and Fig.15.

Feeding time (ms)	7.7	9.1	9.7	10
Projectile position Z(cm)	15	20	22	25
Muzzle velocity (m/s)	65.5	66.8	65.2	64.6

Table.2 : Dependence of muzzle velocity on the feeding time of the second section

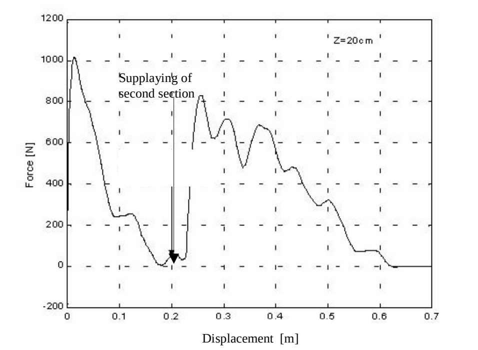

Fig.14 : The propelling force as a function of time, Z=20cm

Capacitor banks feed of the linear induction launcher has the advantages to starting from currents value equal to zero as it was shown in Fig.13. The constant current component in this case doesn't appears.

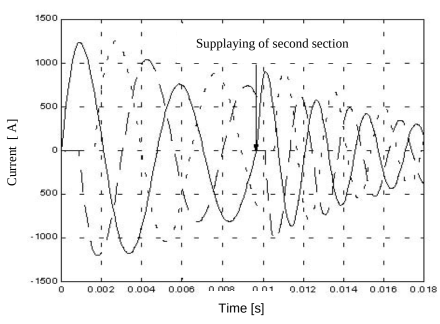

Fig.13 : Two-section barrel currents as a function of time

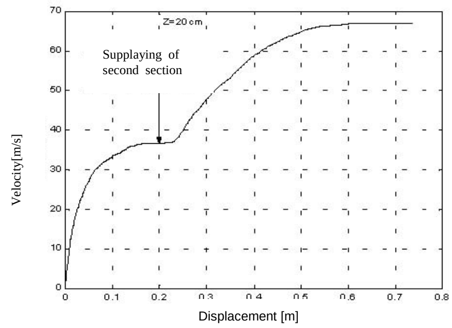

Fig.15 : The projectile velocity profile, Z=20cm

The coupled circuits method used in this article has the advantage of being able to model simultaneously the electric and magnetic phenomena governing the operation of the launcher. Indeed, the model obtained, with this method, expresses the coupling between the projectile and the reels of the inductor, takes into account the relative position of the projectile compared to the barrel and allows the analysis of the behavior of the primary and induced currents . The finite length of the barrel and the projectile is automatically included in the model. The principal disadvantage is that as the number of the elements of the projectile increases, the number of the unknown currents increases and consequently the size of the system of the differential equations also . Thus, the implementation of the method allowed the study and the prediction of the dynamic performances of the electromagnetic induction launcher which are strongly related to its geometrical dimensions and its feeding mode. With this method, the study of the transition between two sections from the launcher was carried out while emphasizing the importance of the parameters which condition this transition such as the primary currents frequency in the barrel coils and the moment of starting of the second section.

The major difference between capacitor and generator supply is that, with the last, upon closing of each switch ordering the discharge of the bank corresponding, the current always starts with zero without dc component. In addition, in the case of the transient discharge, the various phases must be feed by sequence, and the single-phase excitation necessarily occurs after the feeding of the first phase of each section. The undesirable effect due to the single-phasing, can be avoided in the case of the feeding by generators, though at the price of the dc component in the barrel-coils currents. The two types of feeding affect differently the performances of the launcher in the starting section, but even more at the time of the transition from the projectile from one section to the other. However, the feeding by generators, in terms of performance of the launcher obtained, is better than the feeding by capacitive discharge.

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