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Study of Temperature and Frequency Effects in the Performance of a "High Speed Linear Inductive Actuator"

[1]*S.A. Miratashi and* [2]*S.J. Iqbal*

[1]Department of Electrical engineering, University Putra Malaysia, Serdang, Malaysia
[2]Department of Physics, COMSATS Institute of Information Technology, Lahore, Pakistan

Abstract: In this paper the Design, performance analysis and constructing a capacitor driven electromagnetic coil actuator or launcher are developed. Specially, temperature and frequency effects on the value of resistors and capacitors are considered. We have considered all important conditions necessary for the simulation results close to the real cases. To assess simulation results, a small-scale prototype experiment is designed and a linear induction actuator is constructed. The simulation results of theoretical model are in good agreement with the results obtained from prototype experiment. Equivalent electrical circuit model of the coil-launcher provides us a very useful and simple approach to study and analyze them. Mesh matrix model based on the transient circuit analysis gives the insight of coil-gun performance. Furthermore, it is possible to consider temperature and frequency effects in this model. So, a very detailed simulation and analysis is achievable. Our simulations are based on one-section and multi-section coil actuators. It shows that the variable parameters and temperature increasing in drive coils. Capacitors have considerable effects on the performance of the coil-actuator. Power loss in the phase capacitors and their changes due to the frequency variation, is also an important factor in degrading the performance. In this study we have considered the muzzle exit velocity as our main objective performance.

Key words:

INTRODUCTION

The analysis of traveling wave tubular linear induction motors shows that induction is a feasible method of producing armature current and that efficient accelerators can be built without sliding contacts or arcs and offered the potential for extremely high efficiency, flexible, hypervelocity electromagnetic accelerators [1].

Electromagnetic coil actuators or accelerators consists of a barrel formed by an array of coils and of a conductive projectile. (usually aluminum). [2] An accelerating force is provided by the interaction between the magnetic wave produced by the barrel currents and the currents induced in the projectile sleeve. The resulting motion of the projectile is slower than that of the magnetic wave; the difference is termed the slip speed, as in an induction motor. To achieve high efficiency, the swing of the slip speed is limited by subdividing the barrel into several sections. In each section, the frequency of the currents is kept constant but increases from one section to the next, in steps, down the barrel, from the breech to the muzzle.[3]

This paper deals mainly with performance analysis of the capacitor driven electromagnetic coil-launchers using computer simulation. Temperature effects on the conductivity of the sleeve and drive coil resistances are considered.

Mesh-matrix Model and System Equations: Figure 1 is the sketch of a capacitor-driven coil-launcher which consists of two main parts: the barrel and the projectile. It may be driven either by a set of capacitors, as indicated in the diagram, or, alternatively, by a set of AC multiphase sources. The barrel is a linear array of drive coils. The projectile is a conducting sleeve surrounding the payload. The drive coils on the barrel are energized with a certain time sequence, so as to generate a traveling electromagnetic wave that interacts with a system of currents in the sleeve[4-10].

Corresponding Author: S.J. Iqbal, Department of Physics, COMSATS Institute of Information Technology, Lahore, Pakistan E-mail: syedjav@yahoo.com.

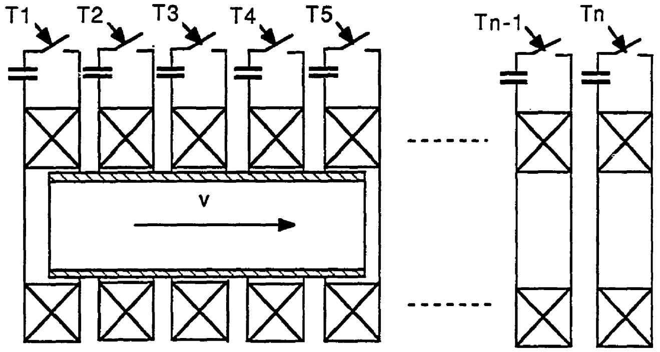

Fig. 1: Sketch of multi-section capacitor-driven coil-gun

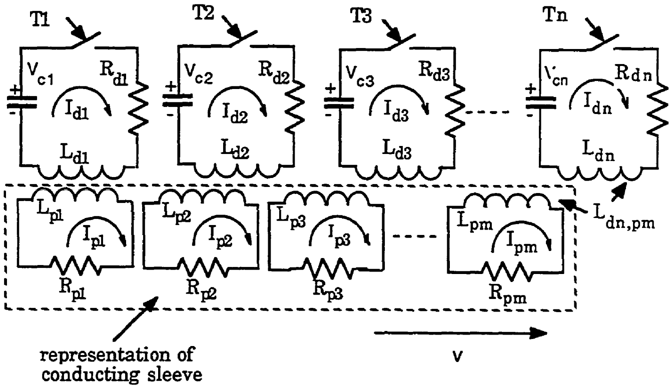

Fig. 2: Lumped parameter circuit model of the capacitor-driven coil-gun

The coil launcher of Figure 1 is modeled by the equivalent circuit shown in Figure 2. Because the axial distribution of the induced current in the sleeve is not uniform, the sleeve is divided into several zones electrically insulated from one another in order to simulate the physical system and is represented by separate projectile coils. The number of coils into which we divide the sleeve depends on the requirement of accuracy. The number of driver coils depends on performance specifications, such as: the muzzle velocity, weight of the projectile, the caliber and the length of the barrel. We denote by N_d the number of drive coils and by N_p the number of projectile coils.

Employing Kirchhoff's voltage law, we write the network equations in the matrix form [6]:

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

Where $[V]$ and [I] are column (N_d $+N_P$ element) matrices composed of the individual projectile and driver coil voltages and currents respectively. $[R]$ and $[L]$ are diagonal ((N_d + N_P) element) matrices composed of the individual projectile and driver coil resistances and self-inductances, respectively and M is a square (N_d + N_P) × (N_d + N_P) matrix each element of which represents a mutual inductance between any two individual coils.

The elements of resistance matrix $[R]$ are calculated as describe in reference [6].

Where a_b and a_s are the thickness, b_b and b_s are the width, r_b and r_s are the average diameter and γ_b and γ_s are the specific conductance of the drive coil and sleeve zone respectively. Also, N_b is the number of turns per coil. The calculation $[L]$ and $[M]$ are described in references [11-14]. It should be noted that the mutual inductances $[M]$ between driver coils and projectile coils are functions of the distance x which denotes the position of the projectile and which is a function of time. This complicates matters considerably. The relations between the capacitor voltages and drive coil currents are [4]:

$$[C]\frac{d}{dt}[V_C]=-[I_d] \qquad (2)$$

The Lorentz force acting on the projectile is given by

$$F=\frac{1}{2}[I]^T G[I] \qquad (3)$$

Where $G=\frac{d}{dx}[M]$ and the superscript v_p stands for the transpose of the matrix. In reference, two methods for calculation of G are described. Finally, we consider the equation of motion and combine it with equations (1), (2) and (3), the complete set of equations which describe the capacitor-driven coil-launcher system is then given in matrix form as follows [6].

$$\{[L]+[M]\}\frac{d}{dt}[I]=[V]-[R][I]-v_p[G][I] \tag{4}$$

$$[C]\frac{d}{dt}[V_C]=-[I_d] \tag{5}$$

$$m_p\frac{d}{dt}v_p=\sum_{p=1}^{N_p}\sum_{d=1}^{N_d}I_pI_d\frac{dM_{dp}}{dx} \tag{6}$$

$$\frac{dx}{dt}=v_p \tag{7}$$

Where m_p is the mass of projectile and v_p is the velocity of the projectile. Equations (4) to (7) represent a set of simultaneous nonlinear differential equations with time-variable coefficients. The number of first order differential equations involved in the system is.

$$N=2N_d+N_p+2 \tag{8}$$

Energy Conversion and Temperature Effects: To assess the performance of the launcher system, one needs first to consider the energy balance relations. This will eventually lead to the optimum design of the launcher. Basically, the energy balance involves several items: the electric energy stored in the capacitor bank, the magnetic energy stored in the coils, the kinetic energy gained by the projectile and the ohmic loss due to the resistances. The main goal in the design of a capacitor-driven coil-launcher is to achieve the transfer of as much as possible of the electric energy stored in the capacitors into kinetic energy of the projectile to attain high system efficiency. The energy relations at time instant t are derived as follow[4]:

$$Wcap(0)-Wcap(t)=Wohm(t)+Wmag(t)+Wconv(t) \tag{9}$$

The force on the projectile is

$$F(t)=\frac{1}{2}\left[I'\right]^T\left[G'\right]\left[I'\right]=\sum_{p=1}^{N_p}\sum_{d=1}^{m}I_dI_p\frac{dM_{dp}}{dx} \tag{10}$$

Since the system is time varying, we define an average acceleration as follows

$$a_{av}=\frac{1}{T_p}\int_0^{T_p}\frac{\sum_{p=1}^{N_p}\sum_{d=1}^{m}I_dI_p\frac{dM_{dp}}{dx}}{m_p} \tag{11}$$

Where T_p stands for the total time the projectile needs to travel along the barrel. This average acceleration, as calculated by the simulation code, is an important quantity for the design of the launcher because it affects the dimensions of the launcher. Another key quantity is the energy transfer ratio, or ETR, which is defined as the ratio of the gain in kinetic energy to the total energy initially stored in the capacitors, because it affects the weight of the capacitor bank.

$$ETR=\frac{W_{kf}-W_{ki}}{W_{cap}(0)}=\frac{W_{conv}}{W_{cap}(0)}=\frac{\frac{1}{2}m_p(v_f^2-v_i^2)}{W_{cap}(0)} \tag{12}$$

Where W_{kf} and W_{ki} refer to the final and initial kinetic energies of the projectile respectively, $W_{cap}(0)$ stands for initial capacitor energy, v_f and v_i are the final and initial velocities of the projectile and $W_{cap}(0)$ is the initial capacitor voltage. Finally, an energy loss ratio or ELR is defined as

$$ELR=\frac{W_{ohm}}{W_{cap}(0)} \tag{13}$$

Another performance measure is capacitor discharge ratio (CDR) which is defined as the ratio of final to initial capacitor energy storage. If one assumes that the launch time is so short that the process is nearly adiabatic, the temperature rise of each projectile coil can be derived from following equation

$$\theta_p(t)=\frac{\int_0^t R_pI_p^2dt}{c_{Al}\,V_{vol,p}} \qquad p=1,\cdots,N_p \tag{14}$$

Where c_{Al} is the specific heat of the Aluminum, material from which the projectile is made and $V_{vol,p}$ is the volume of a projectile coil. Also, for a drive coil, temperature rise can be calculated as follows

$$\theta_d(t)=\frac{\int_0^t R_dI_d^2dt}{c_{Cu}\,V_{vol,d}} \qquad d=1,\cdots,N_d \tag{15}$$

Where c_{Cu} is the specific heat of the Copper, material from which the drive coils are made and $V_{vol,d}$ is the volume of a drive coil.

The temperature in drive and projectile coils affects the resistance and as a result the ohmic loss of the launcher. This can be formulated as

$$R_p = R_{0p}(1+\alpha_{Al}\theta_p(t)) \qquad p=1,\cdots,N_p \tag{16}$$

$$R_d = R_{0d}(1+\alpha_{Cu}\theta_d(t)) \qquad d=1,\cdots,N_d \tag{17}$$

In these equations, R_{0p} and R_{0d} are the resistance of projectile and drive coils at ambient temperature respectively and α_{Al} and α_{Cu} are temperature coefficient of Aluminum and Copper.

In capacitor-driven launcher systems, the capacitor bank not only produces the required energy, but also determines the frequency of traveling wave on the barrel. An electric equivalent schema of an capacitor can be described as an equivalent series resistance (ESR), equivalent series inductance (ESL), the capacitance (C) and a parallel resistance for the leakage current (R_{leak}). R_{leak} depends on the quality of the dielectric [15-16].

When the capacitor is charged and discharged there will be some electrons stored in the dielectric. When the discharge mechanism is removed these electrons start to build up a voltage, i.e. dielectric absorption. If this causes problems, it's possible to get capacitors with a short circuit tape between the terminals. The current through the capacitor will cause a power loss in it, due mainly to the ESR.

$$P_{LossC} = I_{rms}^2 ESR \tag{18}$$

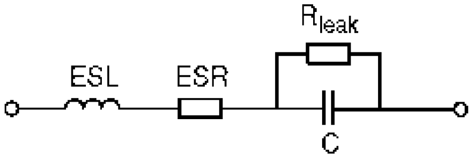

Fig. 3: Electric equivalent schema of a capacitor

ESR is in series connection with resistance of drive coils and it is considered in R matrix. For polyester film capacitors, ESR is calculated as follows [15-16].

$$ESR = \frac{D.F.}{2\pi fC100} \tag{19}$$

Where f is the frequency of Sine, or Near Sine signal, C is the capacitance value and $D.F.$ is dissipation factor of capacitor which is stated in percent. $D.F.$ changes with temperature and frequency and this effects the value of ESR and power loss. The variation of this factor versus temperature and frequency for a metalized polyester capacitor are depicted in Figs. 4 and 5 respectively.

Therefore, ESR increases with increasing frequency. The power loss causes the temperature to go up in the capacitor and this change the value of ESR consequently. The temperature rise in the capacitor can be computed as [6].

$$\theta_{Ci}(t) = \frac{\int_0^t I_{rms}^2 ESR dt}{C_h} \qquad i=1,\cdots,m \tag{20}$$

Where C_h is the specific heat capacitance of the phase capacitors.

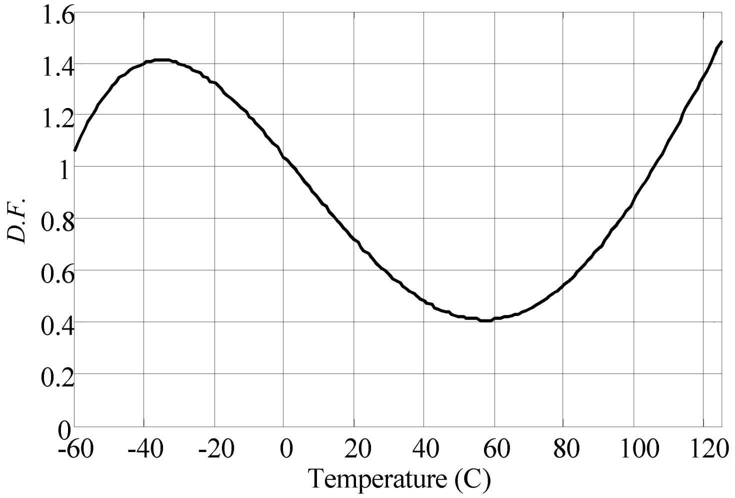

Fig. 4: D.F. as a function of Temperature [6]

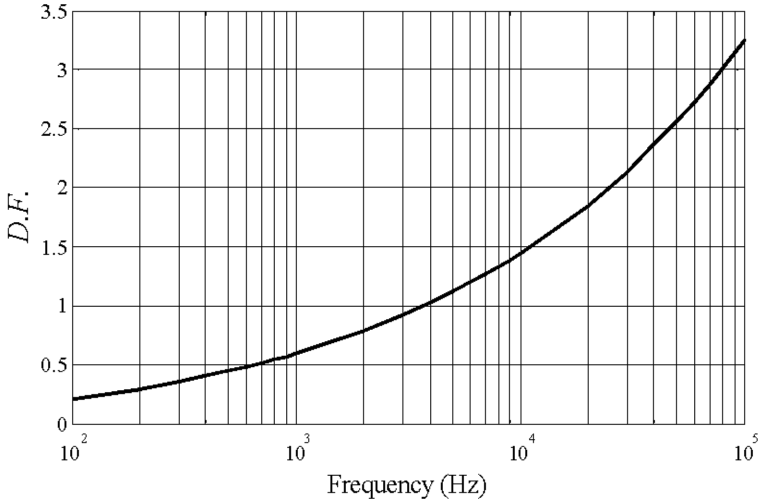

Fig. 5: D.F. as a function of Frequency [6]

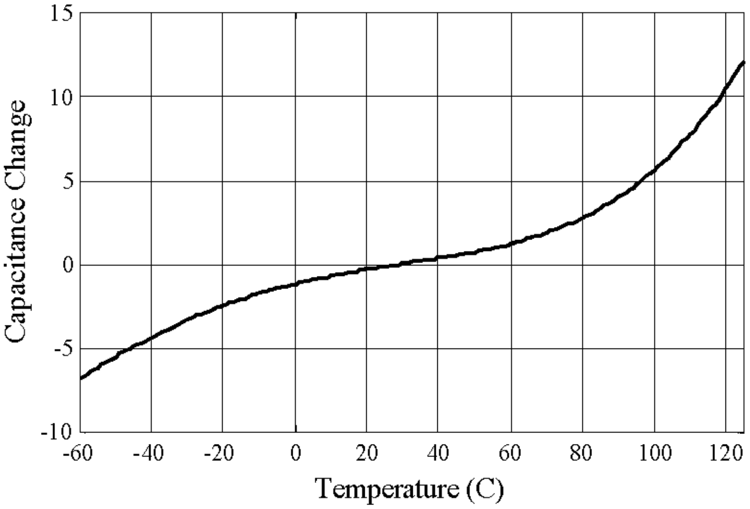

Fig. 6: Capacitance change as a funcion of Temperature [15-16]

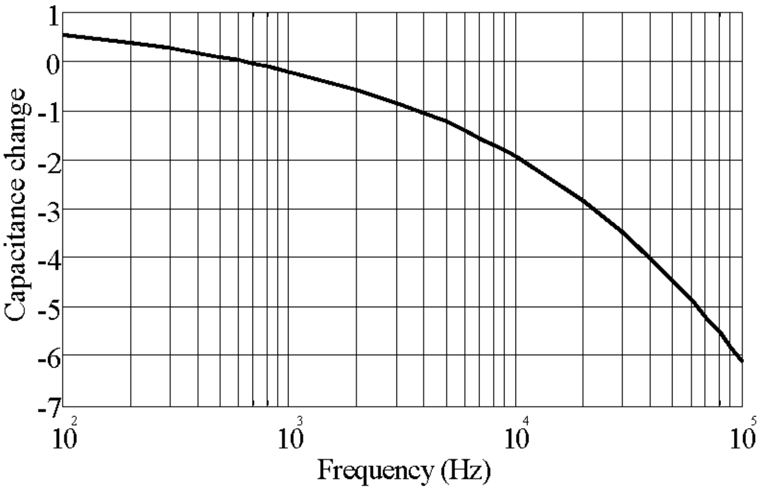

Fig. 7: Capacitance change as a function of Frequency [15-16]

Table 1: Summary of simulation results for 4-section launcher, ideal case

Parameters	Section 1	Section 2	Section 3	Section 4	Total system
Stored capacitor energy (kJ)	13.98	34.85	52.37	54.36	155.57
Peak capacitor voltage	4.50	15 9.5	31.12	39 32.52	
Phases A, B and C	4.31-	-11.62	26.37	-35.28	
(kV)	4.40		-28.5		
Peak current in drive	20.05	42.40	35.47	37.44	
coils, Phases A, B and C	21.90	30.02	33.93	39.21	
(kA)	22.83	36.66	36.45	38.61	
Exit velocity (m/s)	278.45	558.17	867.08	996.18	996.18
Average acceleration (km/s^2)	262.8	299.62	356.5	209.34	277.35
Average force (kn)	32.77	38.11	45.34	26.53	35.27
Energy transfer ratio (ETR) (%)	36.00	42.71	53.49	28.08	40.56
Energy loss ratio (ELR) (%)	46.9	38.8	31.6	27.64	33.2
Capacitor discharge ratio (CDR) (%)	87.3	94.2	89.2	72.4	84.3
Capacitance per phase Phases A, B and C (μF)	3×479	3×154	3×42	3×28	
Frequency (kHz)	1.37	2.62	4.1	5	
Travel time (ms)	1.17	0.93	0.87	0.61	3.59
Switching times of	0 0.24	1.17	2.1 2.19	2.97 3.06	
Phases A, B and C (ms)	0.12	1.30 1.23	2.15	3.02	
Section length in units of pole pitch	2τ	4τ	6τ	6τ	18τ

Table 2: Summary of simulation results for 4-section launcher, real case

Parameters	Section 1	Section 2	Section 3	Section 4	Total system
Stored capacitor energy (kJ)	13.98	34.85	52.37	54.36	155.57
Peak capacitor voltage	4.50	15	31.12	39	
Phases A, B and C	4.31	9.5	26.37	32.52	
(kV)	-4.40	-11.62	-28.5	-35.28	
Peak current in drive	19.91	41.71	34.98	37.41	
coils, Phases A, B and C	21.51	25.87	33.10	35.12	
(kA)	22.55	35.85	35.81	38.10	
Exit velocity (m/s)	266.9	538.2	808.4	922.4	922.4
Average acceleration (km/s^2)	220.9	288.1	308.7	173.2	250.4
Average force (kn)	28.10	36.66	39.22	22.20	31.86
Energy transfer ratio (ETR) (%)	32.42	39.88	44.18	23.1	34.79
Energy loss ratio (ELR) (%)	47.89	33.19	20.76	20.00	25.72
Capacitor discharge ratio (CDR) (%)	87.75	94.67	94.05	88.05	91.52
Capacitance per phase Phases A, B and C (μF)	3×479	3×154	3×42	3×28	
Frequency (kHz)	1.37	2.62	4.1	5	
Travel time (ms)	1.20	0.94	0.87	0.66	3.67
Switching times of	0 0.24	1.17	2.1 2.19	2.97 3.06	
Phases A, B and C (ms)	0.12	1.30 1.23	2.15	3.02	
Section length in units of pole pitch	2τ	4τ	6τ	6τ	18τ

Capacitance value of metalized polyester capacitors also changes with temperature and frequency. In Figure 6 capacitance changes versus temperature and in Figure 7 capacitance changes versus frequency are shown.

Therefore, capacitance value increases with increasing temperature and decreasing frequency.

CONCLUSION

Temperature and frequency effects on the value of resistance and capacitors are considered. We considered all conditions to make the simulation results close to the real cases. Our simulations for one and multi-section coil launchers showed that variable parameters and temperature increasing in drive coils have considerable effects on the performance of the coil-launcher. Power loss in drive coils is due to the high value of current required to traveling electromagnetic waveforms to be created in the barrel. But it increases the temperature of the drive coils and as a result the resistance of the drive coils increases and causes more power loss. Hence, the performance of the coil-launcher degrades and muzzle exit velocity decreases. Power loss in the phase capacitors and their changes due to the frequency variation, is also an important factor in degrading the performance. It should be considered that in a coil-launcher the performance could be considered energy transfer ratio (ETR), muzzle exit velocity, kinetic energy of the muzzle or other factors. In this study we have considered the muzzle exit velocity as our main objective performance.

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