

## Contactless Linear Motor for Maglev Vehicles

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### Introduction

The biggest advantage of magnetic levitation is speed the vehicles handle. No friction between bogie and track eliminates wear but there is still a problem with traction motor. Common linear induction motor consumes power supply bus and pantograph for power delivery. Even for motors that seem to be technically similar. This solution limits maximum speed to 600 km/h approx. A contact less solution is not new by itself, but is not implemented in Linear Induction Motor (LIM) design. It is common in asynchronous rotation motors. Linear motors have huge advantage, if talking about serviceability. Normally, they do not need service. So in this design goal is to develop whole lifetime non-serviceable motor with expected lifetime (runtime) of 50 years.

### Predefined requirements

This motor must comply with several requirements to be effective for MAGLEV vehicles. It must provide enough traction power for good acceleration. For calculations we assume, that vehicle weight will be 32 tons approx. It is supplied with 2 secondary elements. To reach high-speed motion in short time, maximum acceleration must be 2,5 m/s<sup>2</sup>, to keep comfort levels. This acceleration is equal to Boeing 737 acceleration during lift-off. To avoid border effects, that are familiar in most common LIM designs, it is proposed to use time divided power impulses. Section is active when active surface of the core  $s > 0$ . To avoid losses due border effect, it is proposed to apply power when  $s$  is greater or equal to 1/6 of  $s_{max}$ , where

$$s_{max} = l \cdot d ,$$

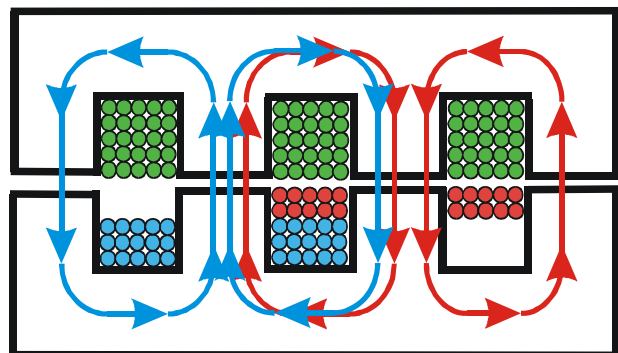
because linear motor magnetic system consumes significant amount of space, and for calculation ease,  $d$  – width of the core, is 1 meter for both parts. In the Figure 1, shape of the core pole is not given, but due to the large air-gap, distance between poles must be much greater, than air-gap or must be filled with magnetic insulator. The characteristic air-gap for magnetic levitation vehicles is  $h_g = 10 \pm 2$  mm. Length of the core  $\Lambda = 2,5$ m

### Motor structure

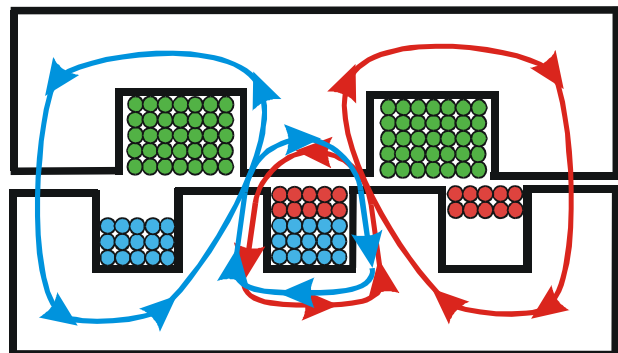
In fact, there are still some major disadvantages in

linear motor design - a large air gap between windings and significant energy losses due to border effect. Regular way to create LIM is to place a massive track element and place windings on bogie. Approach is to build track from comparably small sections that contain propulsion windings (primary) and bogie is equipped with secondary winding. Most complex task is to choose correct design of a core. Symmetrical (Fig.1a) or asymmetrical (Fig.1b) pole designs with magnetic flux paths are shown.

Both designs have advantages and disadvantages. Symmetrical design provides higher maximum peak flux but suffers from border effect (if not avoided) and causes high frequency distortion appearance in windings.



**Fig. 1a.** Symmetrical core motor.



**Fig. 1b.** Asymmetrical core motor.

### Parameter description

Asymmetric design is harder to describe mathematically due to magnetic flux path and magnetic

force is lower than in symmetric design. In both cases mathematical basis is similar, but flux equations differ.

Traction force is described with formula [2]

$$F_{EM} = \frac{k_w l}{\sqrt{2}} 2 p \tau_i A B_{\delta I} \cos \varphi_{EM}. \quad (1)$$

Speed can be calculated by the same way as for other linear motors [3]

$$V = 2 \tau f. \quad (2)$$

That shows - high-speed sections it is necessary to manipulate with quite high frequencies or change distance between poles. Because we cannot change core design for secondary part, it is necessary to calculate both - symmetric and asymmetric designs.

These calculations can be based on work, each segment does. Because work is relative to applied force in a predefined distance, we can talk about relative speed and relative acceleration. If we define the values:

- $t_n$  – section power-on momentum;
- $\delta_n$  – section power-on time;
- $F_n$  – Acceleration force;
- $F_c$  – Motion resistive force;
- $g(t)$  – mechanical system describing function.

Then relative speed can be expressed

$$V(t) = \begin{cases} V(t_n) + \int_{t_n}^t g(t-\tau) F_n(V, \tau) d\tau; t_n \leq t \leq t_n + \delta_n, \\ V(t_n + \delta_n) - \int_{t_n + \delta_n}^t g(t-\tau) F_c(V, \tau) d\tau; t_n + \delta_n \leq t \leq t_n + T_n, \end{cases} \quad (3)$$

where  $T_n$  is a period between traction impulses and this can be calculated as a minimum root from equation

$$\int_{t_n}^{t_n + T_n} V(\tau) d\tau = \Delta, \quad (4)$$

where  $\Delta$  is distance between powered sections. Section power-on time can be determined by a rule from active length of a section -  $l_a$

$$\int_{t_n}^{t_n + \delta_n} V(\tau) d\tau = l_a. \quad (5)$$

Because there are two versions of primary section – symmetric and asymmetric, then there persist two lengths of a section. Traction force is relative from length of a shortest section –  $l_m$  and can be expressed from Kloss formula

$$F_n = \frac{F_k s_k (1-V)}{s_k^2 + (1-V)^2} \left\{ \begin{array}{l} \frac{V_0}{l_m} \int_{t_n}^t V(\tau) d\tau [(t-t_n) - (t-t_n - \Theta_n)] + \\ \frac{V_0}{l_m} \int_{t_n}^t V(\tau) d\tau [(t-t_n - \Theta_n) - (t-t_n - \delta_n)] \\ - \frac{V_0}{l_m} \int_{t_n + \nu_n}^t V(\tau) d\tau [(t-t_n - \nu_n) - (t-t_n - \delta_n)] \end{array} \right\} - F_c, \quad (6)$$

where  $F_k$  is critical force and  $V_0$  is synchronous speed.

Time momentums  $\Theta_n$  and  $\nu_n$  are set from rules

$$\int_{t_n}^{t_n + \Theta_n} V(\tau) d\tau = l_m; \quad \int_{t_n}^{t_n + \nu_n} V(\tau) d\tau = l_a - 2l_m. \quad (7)$$

Besides traction force to speed calculations, it is necessary to calculate electrical parameters. As it is defined in formula 1, traction force is relative to flux density in air gap, coil winding count quotient, pole division in primary and secondary part. Magnetic flux from single pole of the motor can be expressed

$$\Phi = B_{avg} l \tau, B_{avg} = \frac{2B_{max}}{\pi}. \quad (8)$$

Magnetic flux in one pole is created by 2 phase current. Angle between winding currents is  $90^\circ$ . Because position is not fixed, only momentum values can be calculated. So force momentum is

$$F = \frac{\mu_0 I I}{s},$$

where

$$I = \sqrt{I_1^2 \cos \varphi + I_2^2 \cos(\varphi + 90^\circ)}. \quad (9)$$

This mean, that one coil is creating magnetic field while second coil is creating interaction force.

System can be replaced with equivalent schematics similar to regular rotation asynchronous motor. So impedance for each coil is

$$\begin{aligned} z_1 &= r_1 + jx_1, \\ z_2 &= r_2 + jx_2, \\ z_s &= r_s + jx_s. \end{aligned}$$

Voltage, that is necessary to apply, can be expressed as

$$\dot{U} = E \left[ 1 + \frac{z_1}{z_s} + \frac{z_1}{z_2} \right], \quad (10)$$

where E is EMF.

In fact, due to crosswise force, the effective traction force from one square unit ( $N/m^2$ ) is

$$\partial F_{EF} = \frac{\partial F^* \xi}{\Lambda^* d}, \quad (11)$$

where

$$\xi = \frac{1}{1 - \frac{2}{\pi \frac{l}{\tau} \left[ \operatorname{tg} \left( \frac{d_{pri} - d_{sec}}{\tau} \right) + \operatorname{ctg} \left( \frac{\pi^* d_{pri}}{2\tau} \right) \right]}}.$$

Flux density instantaneous momentum value is reversibly expressible from traction force

$$B = \frac{2\sqrt{2}\xi F}{2\rho H s}.$$

From here I conclude, that effective momentum value of the electric propelling force for coil is

$$E_i = 2\sqrt{2} f w_i k_{w_i} B d = 4 f w_i k_{w_i} \frac{\xi F}{\rho H}. \quad (12)$$

## Pole square calculations

For pole shape choice and other calculations it is necessary to understand, that most resistive medium for magnetic flux, is air-gap. This gap is large enough, to eliminate magnetic saturation in core metal and losses in this gap is much bigger, than in core.

In our case one pole  $s_{\max}$  for symmetric core is calculated from assumption, that distance between poles  $l_p$  is

$$l_p = \frac{\pi h_g}{\sqrt{2}}. \quad (13)$$

Pole square maximum then is

$$s_{\max} = \left[ \frac{\Lambda}{p} - l_p * (p-1) \right] * d. \quad (14)$$

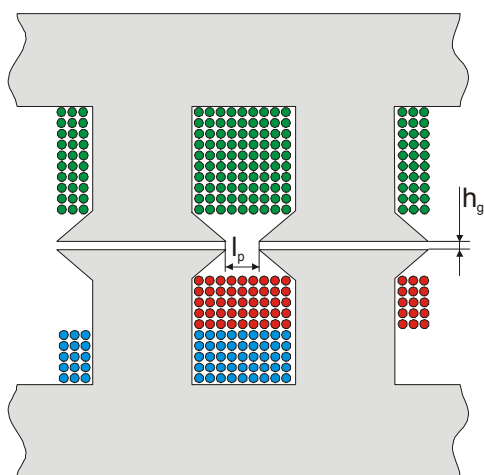


Fig. 2. Primary and secondary core pole shape

In Fig. 2 only approximate shape design is proposed, that permits highest efficiency for traction.

## Speed calculations

For an example, if  $\Lambda=2,5\text{m}$  ( $V_0=f\Lambda$ ), linear speed (or synchronous speed) of a run-field is given in Table 1.

Table 1. Run-field linear speed relative to frequency.

Frequency (Hz)	Synchronous Linear speed (m/s)	Synchronous Linear speed (km/h)
10	25	90
25	62,5	225
50	125	450
100	250	900
<b>132,56</b>	<b>331,4</b>	<b>1193,04</b>
200	500	1800
400	1000	3600
600	1500	5400
800	2000	7200
1000	2500	9000

From Table 1 it is easy to understand that for speed close to MACH 1 (gray row), power frequencies are kept in levels, where coil inductive resistance is in acceptable levels. If core geometry is changed, speed relatively to

frequency changes. Frequencies for speeds above MACH1 are given while looking ahead to intercontinental transportation, particularly to transatlantic tunnel.

## Traction force requirements

From predefined requirements we see, that each motor must be capable to push vehicle at top acceleration level, that is  $2,5 \text{ m/s}^2$ . So there is 16t payload for each motor. That means  $F_{EM}$  is less or equals to 40kN traction force per motor, for acceleration, plus physical resistance force (friction to air). From here we see, that power consumption from source at speeds close to MACH 1 will be 13,3MW approx. Let's assume that power supply voltage is 25kV and that mean 532A currents in windings.

## Conclusions

Because only totally contact-less linear motors can reach speeds over 600 km/h, such linear motor design is useful for high-speed transportation. From pole active square calculations and pole design it is clear, that symmetrical design suits better for high speed sections and due to its higher peak traction force value, is better for acceleration and deceleration sections. Asymmetric design has advantages in slow motion sections while traction is applied much smoother than in symmetrical design. Traction smoothness can be achieved also by symmetrical design with adapted coil power-on timing. Speed regulation requires changing currents in secondary winding, that can be done using inverters, but calculations depend on coil parameters. This regulation effect permits to use energy from secondary winding for on-board devices so a total contact-less solution is achieved.

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**O. Krumins. Contactless Linear Motor for MAGLEV Vehicles // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 7(71). – P. 9–12.**

In this paper theoretical design of a new sort of linear motor is described. By design this motor permits to reach high speed motion while no mechanical limitations persist. Such motor design advantage is absence of pantograph or any mechanical contact between bogie and the track. Mathematical apparatus for motor calculations are given. Basic calculations have been made basing on parameter example that can be close to real. Two motor core designs are proposed and evaluated. Shape of a pole is a case of a closer research to find best parameters. Ill. 2, bibl. 6 (in English; summaries in English, Russian and Lithuanian).

**О. Круминьш. Бесконтактный линейный двигатель для подвижных единиц на магнитной подушке // Электроника и электротехника. – Каунас: Технология, 2006. – № 7(71). – С. 9–12.**

Представлено теоретическое описание проектирования двигателя нового типа. Такой двигатель позволяет достичь большую скорость движения при отсутствии механических ограничений. Преимущество мотора заключается в том, что между рельсами и коляской нет держателей или механического контакта. Представлена математическая модель расчета параметров двигателя. Произведены основные расчеты. В расчетах применены примерные параметры могут быть приближены к реальным. Предложены и оценены два варианта сердцевины двигателя. При выборе лучших параметров нужны дальнейшие расследования формы полюса. Ил. 2, библи. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

**O. Krumins. Bekontaktis tiesinis judžių objektų su magnetine pagalve variklis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – Nr. 7(71). – P. 9–12.**

Teoriškai aprašomas naujo tipo tiesinio variklio projektavimas. Pagal projektą šiuo varikliu galima pasiekti didelį judėjimo greitį, kol nėra jokių mechaninių apribojimų. Tokio variklio projekto pranašumas yra tai, kad tarp bėgių kelio ir vežimėlio nėra jokių laikiklių ar mechaninio kontakto. Pateiktas matematinis variklio parametrų skaičiavimų modelis. Atlikti pagrindiniai skaičiavimai. Skaičiavimuose naudoti pavyzdiniai parametrai gali būti artimi realiams. Pateikti ir įvertinti du variklio šerdies variantai. Norint nustatyti geriausius parametrus, reikia tęsti poliaus formos tyrimus. Il. 2, bibl. 6 (anglų kalba, santraukos anglų, rusų ir lietuvių k.).

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