LINEAR SYNCHRONOUS MOTOR DESIGN USING FEM

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***Abstract* – The development of a linear synchronous motor prototype for a levitating vehicle is shown in this paper. As the design of this kind of motor diverts from that of a conventional machine, the feasibility and usefulness of the Finite Element Method (FEM) assistance in the design is studied. The current state of the prototype under construction at UFRJ is also presented.**

KEYWORDS

Linear Motors, Finite Element Analysis

I. INTRODUCTION

The use of linear traction for transportation vehicles is necessary when some kind of levitation mechanism is used because it would not be possible to transmit traction force to the vehicle without wheel-on-rail contact. The levitation bearings can be electromagnetic, electrodynamic or superconducting. The superconducting type is the most recent one and raised from the possibility of achieving superconductivity at liquid nitrogen temperature (77K), using ceramic materials like YBCO composites.

In order to study the combined operation of the superconductor bearings and the linear traction, a first prototype was built and tested. This one consisted of a straight rail of 7 meters long, using short stator synchronous motor with sliding contacts. The choice of a synchronous motor instead of an induction motor was based on the possibility of working with larger airgap and a simpler control scheme. This prototype used Ferrite magnets on the motor field and on the levitation bearings.

The tests carried out with this prototype showed that the levitation force produced by the diamagnetic interaction between the YBCO blocks and the Ferrite magnets was not strong enough to produce levitation. Then a new prototype was considered, using Nd-Fe-B magnets replacing the Ferrite. This new prototype consists of a closed path of 30 meters long, as shown in Figure 1. The synchronous motor is planned to be built on the straight parts of the track, with long armature distributed along the rail and field magnets on vehicle.

As the levitation force produced by the superconducting bearings is also under test, it was decided to use an air cored armature winding to reduce the attraction force between the vehicle and the track. This suggests the use of an enhanced excitation system, so Nd-Fe-B magnets were also used in the motor field. For the sake of a simpler construction, a flat, single sided motor configuration was chosen.

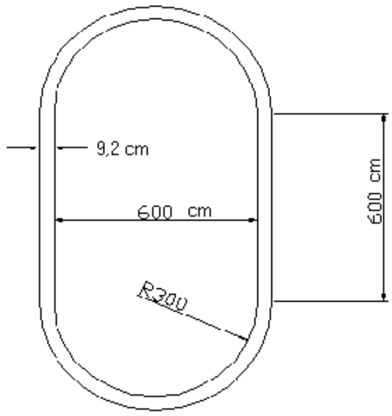

Fig. 1 - Closed path track

II. DESIGN APPROACH

The design of the motor was based on equivalent-circuit derived analytical equations (1) through (4) with critical parameters estimated by FEM.

$$F_{dx} = \frac{P_{elm}}{v_s} \tag{1}$$

$$P_{elm} = m_1 \cdot I_{aq} \cdot E_f \tag{2}$$

$$E_f = \pi \cdot \sqrt{2} \cdot f \cdot N_{esp} \cdot k_{w1} \cdot \phi_g \cdot \left(\frac{p_{car}}{2}\right) \tag{3}$$

$$I_{aq} = \frac{V_1 \cdot (R_1 \cdot \cos\delta + X_s \cdot \mathrm{sen}\,\delta) - E_f \cdot R_1}{X_s^2 + R_1^2} \qquad (4)$$

where

F_{dx}: traction force;
v_s: synchronous speed;
P_{elm}: converted electromagnetic power;
m_1: number of phases;
E_f: counter-electromotive force;
I_{aq}: quadrature axis armature current;
f: frequency;
N_{esp}: number of turns per coil;
k_{w1}: winding factor;
ϕ_g: flux per pole;
p_{car}: number of poles on vehicle;
R_1: per phase armature resistance;
X_s: per phase synchronous reactance;
V_1: terminal phase voltage;
δ: load angle.

In the above equations, the parameters ϕ_g and L_s (synchronous inductance corresponding to X_s) are calculated using FEM. As it is shown in the following sections, it is also possible to perform a FEM direct calculation of traction force and to compare this result with the force calculated through equations (1) to (4).

III. FEM CALCULATIONS

A. Flux per Pole

The flux per pole is directly calculated through an area under the pole in the 3-D model of the motor, as shown in Figure 2.

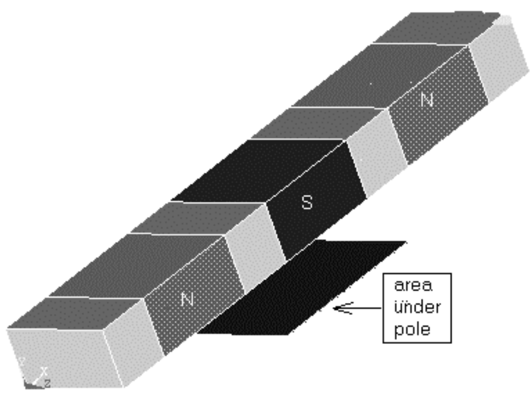

Fig.2 - Flux per pole FEM calculation

This area is defined by the pole pitch and the active length of the armature winding conductors under the poles.

B. Synchronous Inductance

The synchronous inductance is calculated from the self and mutual inductances of a set of three coupled coils as shown in Figures 3a and 3b.

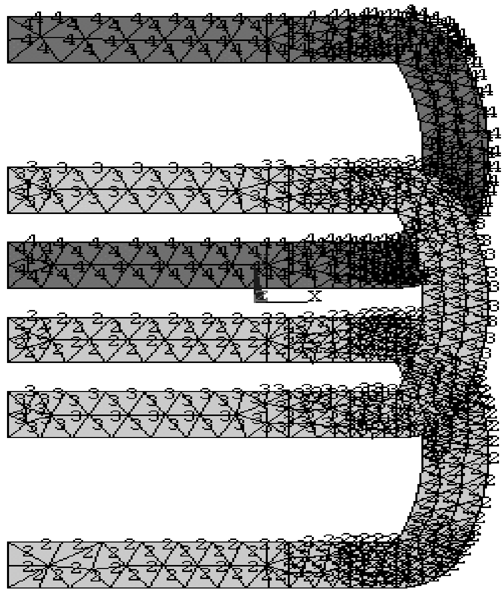

Fig. 3a: Coupled coil set, top view

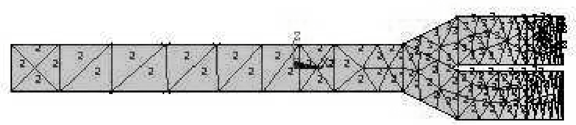

Fig. 3b: Coupled coil set, side view

For a linear motor, the relationship between synchronous inductance and phase inductances can be described by

$$L_s = L_a - L_{ab} \qquad (5)$$

where

L_a is the self-induction of a phase and L_{ab} and L_{ac} are the mutual inductances between phases, considering that for a long armature winding

$$L_{ab} = L_{ac} \tag{6}$$

C. Traction Force

The traction force is calculated by FEM considering a 3-D model where the conductors are fed with time-varying three phase set of currents (Figure 4). Sequential solutions are calculated for successive time intervals in such a way that the spatial displacement between the magnetic field produced by the permanent magnets on vehicle and the field produced by the armature changes with time, thus simulating the variation of load angle δ. The force was calculated over the conductors on track using

$$F = J \times B \tag{7}$$

and

$$F_{track} = -F_{vehicle} \tag{8}$$

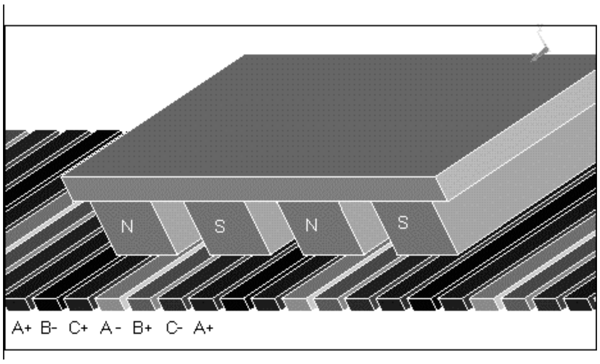

Fig. 4 - 3-D model used for thrust calculation

IV. EXPERIMENTAL RESULTS

To check the validity of using FEM support in the design of this motor, two different tests were performed, designed to evaluate the inductance and force calculation.

A. Inductance Results

The self-inductance of one coil of the armature winding, calculated using a 3-D model, can be compared with the measured value, as shown in Table I.

TABLE I
Self-Inductance Results

Parameter	**FEM Result**	**Measured Value**	**Error**
Self Inductance	38.1 μH	39.5 μH	3,5 %

B. Traction Force Results

As the closed path track described above was not yet available for tests, a section of the rail with one meter long armature winding and 4 poles of Nd-Fe-B permanent magnets on vehicle, shown if Figure 5, was used to perform the traction force measurement. This was accomplished by feeding the armature with DC current and forcing the vehicle to displace from a rest position.

Tests were taken for armature current values of 2.5, 5.0 and 10.0 A. Due to limitations of the measurement apparatus, the best results readings were obtained for the higher values of current and force (I = 10 A). This results are shown in Figure 6. The new track at the moment under construction at UFRJ is shown in Figure 7.

Fig. 5 - Armature winding

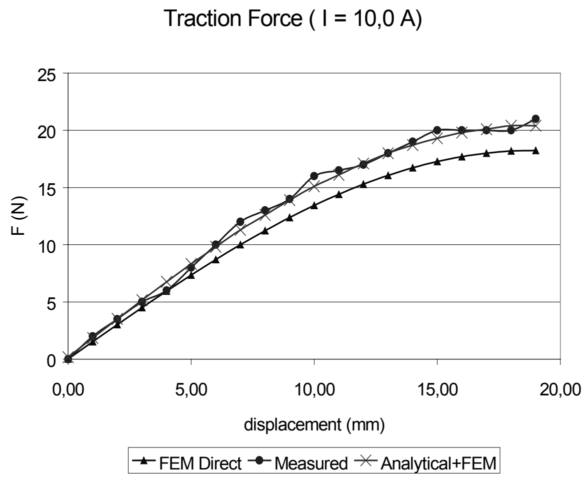

Fig.6 - Experimental results for traction force

Fig. 7 - Prototype under construction

V. CONCLUSION

The FEM support in the design of the linear synchronous motor prototype presented here was applied in three specific subjects: flux, inductance and force calculation. The FEM proved to be a effective design tool in each case.

Flux determination is a critical detail in any motor design. The FEM calculation of flux in the present case was very useful, since this motor has a unconventional shape in the magnetic circuit and is subject to airgap length variation due to the levitation / traction arrangement.

The 3-D FEM modeling of the coils allowed the end-winding connection effect to be considered in inductance calculation, avoiding the use of complex analytical expressions. These expressions were created from the study of conventional machines and the work with FEM will help to clarify up to which extent they are valid for linear machines. The FEM estimated values for self-inductance showed a good agreement with the measured ones.

Concerning the traction force estimation, the preliminary tests suggests that both the combined analytical plus FEM approach (introducing parameters calculated by FEM into analytical equivalent-circuit derived equations) and the FEM direct calculation approach lead to results close to experimental values.

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