Electrical performance of two different types of Permanent Magnet Linear Synchronous Machines with vector control

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Abstract

There is a dilemma about employing or not employing iron in the primary core of synchronous linear actuators. To give some guidance about the convenience of using iron or ironless primary cores, two prototypes of Permanent Magnet Linear Machines (PMLSM) geometrically identical were built. The prototypes were tested in order to get reliable comparative conclusions.
The purpose of this paper is to analyse the performance of two different topologies of linear synchronous machines, using vector control techniques. Several tests were performed to determine the electromagnetic properties and the static forces of the prototypes involved. The paper concludes with a discussion of their performances and dynamics, and their suitability for different applications.

1 Introduction

Linear electrical machines are normally used in special applications, or where a task requires a dynamic performance that rotary machines are unable to provide. They provide direct drive, converting electromagnetic energy directly into thrust and linear displacement, without any intermediate mechanical element.
The same topologies exist for linear machines as for their rotary counterparts. Among these, Permanent Magnet Linear Synchronous Machines present some advantages over Linear Induction Machines (LIM), such as bigger thrust / size ratio, more efficiency and faster response [1]. These special characteristics make synchronous machines suitable for tasks that need an exigent dynamic performance (high speed and acceleration). However, PMLSMs and LIMs require more sophisticated control strategies than rotary machines, affordable recently with the development of power and control electronics.
In this paper an iron cored PMLSM and a non-magnetic cored PMLSM are compared in order to determine their advantages and disadvantages in position control.

2 Description of the prototypes

Linear and rotary machines have some similar constructive characteristics. In both, primary windings are supplied with current to create a travelling magnetic field, and secondary magnetic flux is generated by permanent magnets placed on a secondary iron core. The interaction between both fields generates the thrust (or torque, if we are referring to rotary machines) required for movement.
The two analysed prototypes also have the same physical dimensions. The only difference between them is the material of the primary core. One has a ferromagnetic material core, whilst the other has a non-magnetic primary core. Figure 1 shows the structure of both prototypes. Guides and supports have been designed to facilitate experimental tests, and optimise analysis tasks.

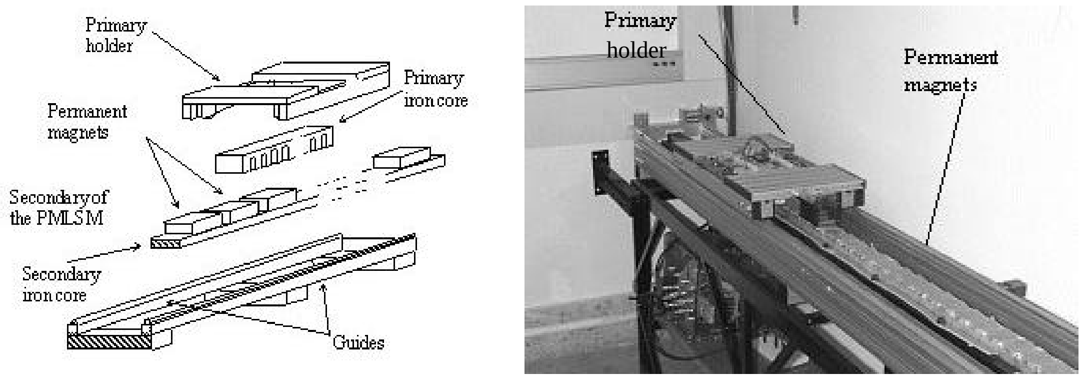


Figure 1. Prototype structure. View of the PMLSM

Table 1 summarizes the constructive characteristics of both prototypes. All the characteristics are identical, except that of the material of the primary core.

2.1 Primary part

In the iron cored PMLSM, iron is used to maximize the production of magnetic flux. As the machine has a large airgap, the value of the inductance is low, L_s = 90 mH.
The prototype has a solid iron core with 28 teeth and 27 slots. The core has a width of 50 mm. The remaining physical dimensions are shown in Table 1. Figure 2 shows the disposition of the prototype.
The ironless PMLSM has the same structure (Figure 2), but its primary core is made of a non-magnetic material.
The inductance of the ironless PMLSM is L_s = 23.14 mH. The absence of iron notably decreases the inertial mass, but also decreases the inductance L_s. The masses of the prototypes are 14.96 kg for the PMLSM with iron armature, and 11.29 kg for the ironless PMLSM.

Table 1

	Iron core armature PMLSM	Ironless armature PMLSM
type	Three phase	Three phase
Primary		
Turns/coil	225	225
Armature material	iron	ironless
Pole pitch (τ)	50 mm	50 mm
Slot pitch	16.6 mm	16.6 mm
Secondary		
Material	Rare earth magnets (SmCo)	Rare earth magnets (SmCo)
Airgap (g)	8 mm	8 mm
Height of magnets	8 mm	8 mm
Width of magnets (τ_b)	37 mm	37 mm

2.2 Secondary part

The secondary of both prototypes is composed of permanent magnets placed on a secondary iron core (Figure 2). Rare earth magnets (SmCo) were employed, due to their high energy / volume ratio.
It is very important to exploit the optimal width of the permanent magnets in order to minimize the non-linearities in the production of force (detent force). There are two main causes of detent force [2]. The first is a consequence of the interaction that is present between the primary iron core and the magnets (cogging). The second involves the interaction of the first harmonic components of both electromagnetic fields. In ironless PMLSMs, only the second cause need be taken into account, because there is no interaction between the magnets and the primary iron [1][2].

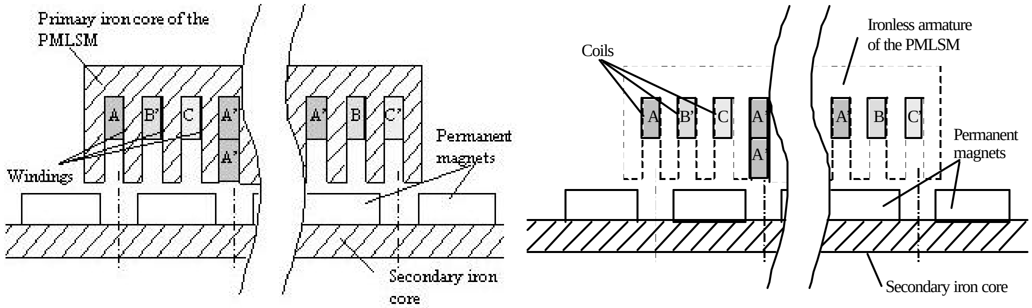


Figure 2. PMLSM with iron armature and PMLSM with ironless armature schemes

3 Method of analysis

3.1 Vector control

Field Oriented Control was employed to control both prototypes. Figure 3 shows the control scheme that was used. All the control loops work with PI controllers, with the exception of the position loop, where a P controller is used.

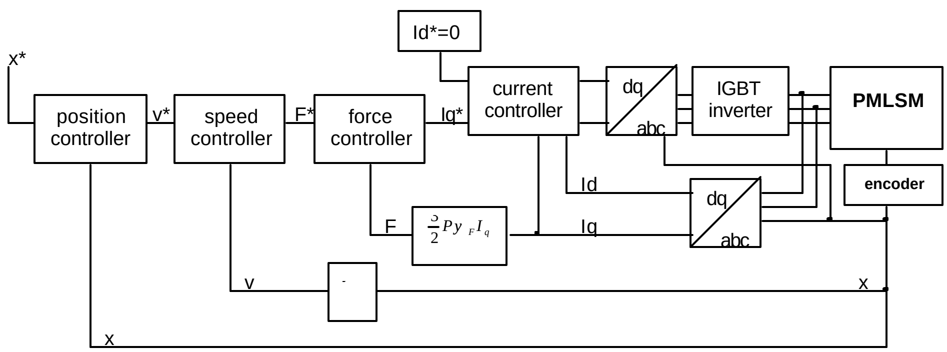


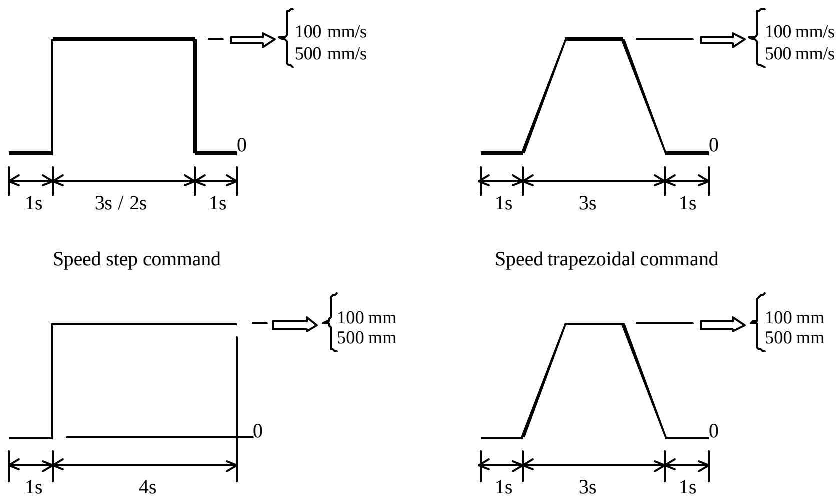
Figure 3. Control block diagram

3.2 Power system

The control algorithm has been implemented with a DSP Controller board, whilst the power system consists of a three phase IGBT inverter with a DC-bus voltage of 310 V. The PWM is performed at the switching frequency of 5 kHz.

3.3 Description of the tests

The prototypes were tested in order to characterise the efficiency of their electromagnetic energy conversion. Their thrust, speed, precision and power consumption features were then analysed. The purpose of the analysis has been to determine the advantages and disadvantages of prototypes, as they perform tasks with diverse requirements of accuracy, rapidity, stiffness, etc. Speed and position tests were carried out, using the reference commands shown in Figure 4. In total, the results of 8 tests are presented: 2 speed tests and 2 position tests with step reference commands, and 2 speed tests and 2 position tests with trapezoidal reference commands.



Speed step command

Speed trapezoidal command

Position step command

Position trapezoidal command

Figure 4. Reference commands

4 Results

4.1 Thrust

The thrust was tested in the two PMLSM prototypes. Both machines were supplied with V = 90 V DC, and the static thrust was measured (Figure 5). The ratio of maximum thrust for ironless PMLSM and PMLSM with iron armature, both excited with the same NI product, is 4.76, a value close to the ratio of their inductances. L_s = 90 mH in the case of the iron cored PMLSM, and L_s = 23.14 mH in the case of the ironless PMLSM.

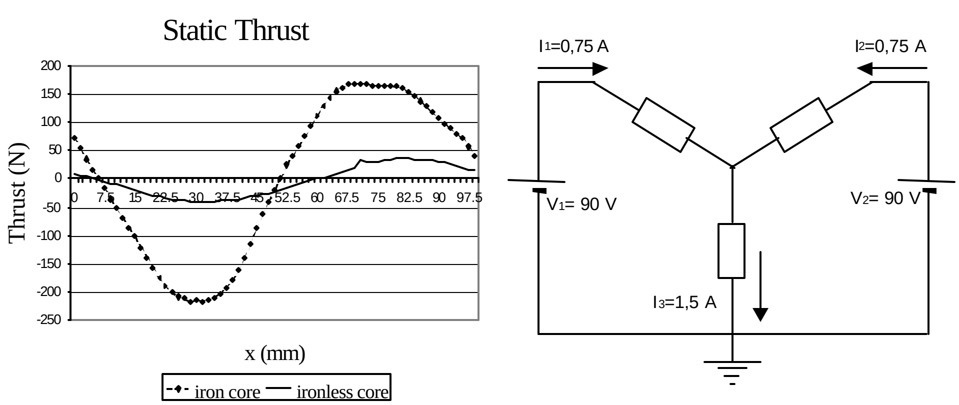


Figure 5. Static forces. V_{supply} = 90 V DC. v = 0 m/s

4.2 Speed tests

Figure 6 shows the speed response and power consumption of both prototypes under step commands of 100 mm/s and 500 mm/s respectively.

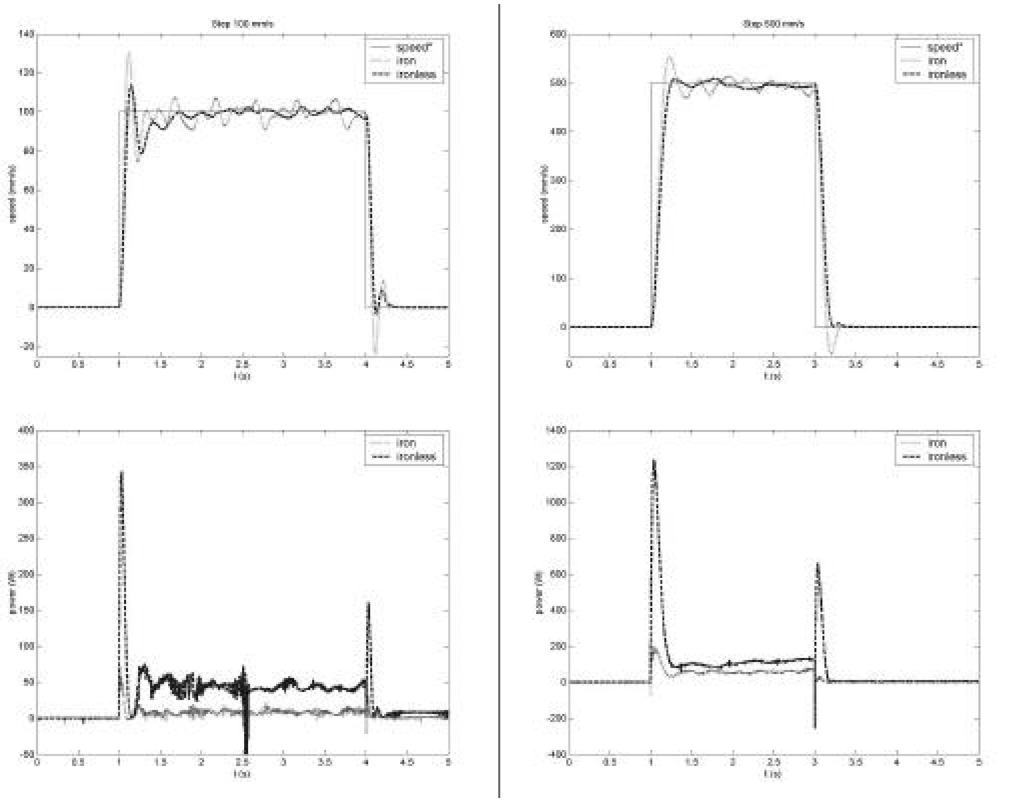


Figure 6. Speed response and power consumption with 100 mm/s and 500 mm/s step commands

Looking at the diagrams, it can be noticed that:

- Using the same control scheme and the same power system, there is not big difference between their settling times (Table 2).
- There is a higher power consumption for the ironless PMLSM. It needs an average current excitation 3.89 times bigger than the iron cored prototype to produce the same thrust. In other words, given the same current excitation for both machines, the force developed by the iron cored PMLSM is about 4 times higher.
- Force ripple, and consequently speed ripple, are more significant in PMLSMs with iron armature. In ironless machines there is no cogging force and no interaction between magnets and primary iron, but force ripple does not disappear completely. There is an interaction between the first harmonic components of primary and secondary magnetic fields. Therefore, without a force ripple compensation system, it is difficult to achieve high speed and positioning accuracy in iron cored PMLSMs. Figure 7 shows the speed ripple in both machines in more detail. For a 100 mm/s speed command, the speed relative average errors are 11 % and 2.5 % in iron cored PMLSM and ironless PMLSM respectively. For a 500 mm/s command, those percentages decrease to 3.6 % and 1.5 %.

Table 2

	PMLSM with iron	PMLSM ironless
Step 100 mm/s	0.075 s	0.13 s
Step 500 mm/s	0.165 s	0.245 s

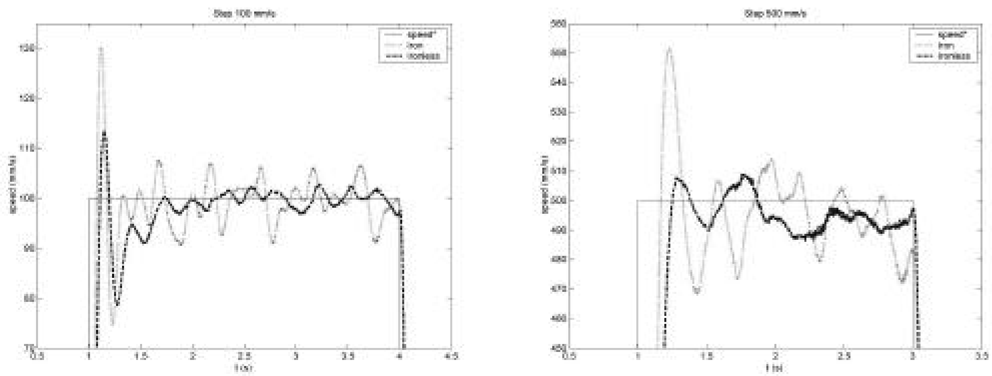


Figure 7. Speed response with 100 mm/s and 500 mm/s trapezoidal commands (detail)

Figure 8 shows the results of a similar test, this time with trapezoidal speed commands. The response has the same characteristics as in the former case, and the same observations can be made. It can be seen that iron cored PMLSMs have more problems travelling with constant acceleration.

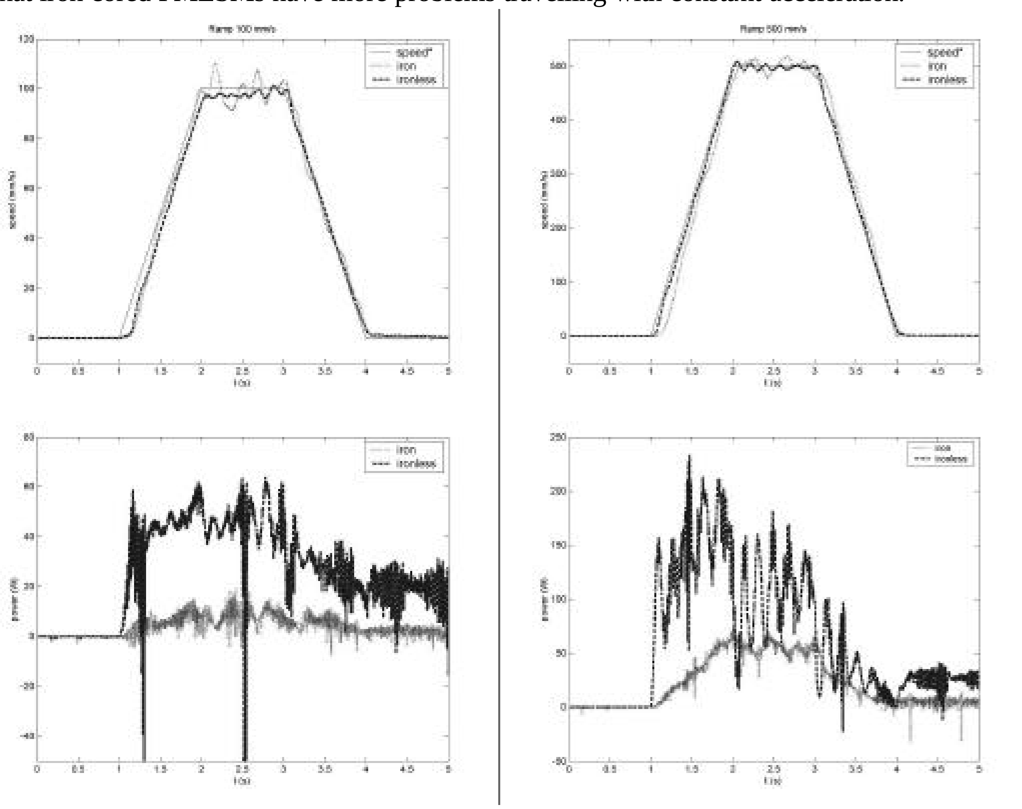


Figure 8. Speed response and power consumption with 100 mm/s and 500 mm/s trapezoidal commands

4.3 Positioning tests

Experimental tests with step position commands and trapezoidal position commands were performed. Figure 9 and Figure 10 show the results of the step command tests and the trapezoidal command tests respectively. Both prototypes reach similar speed and acceleration features, but the power needed by the ironless PMLSM is considerably higher. Speed ripple in the iron cored machine causes irregularities and undesirable oscillations in the position response.

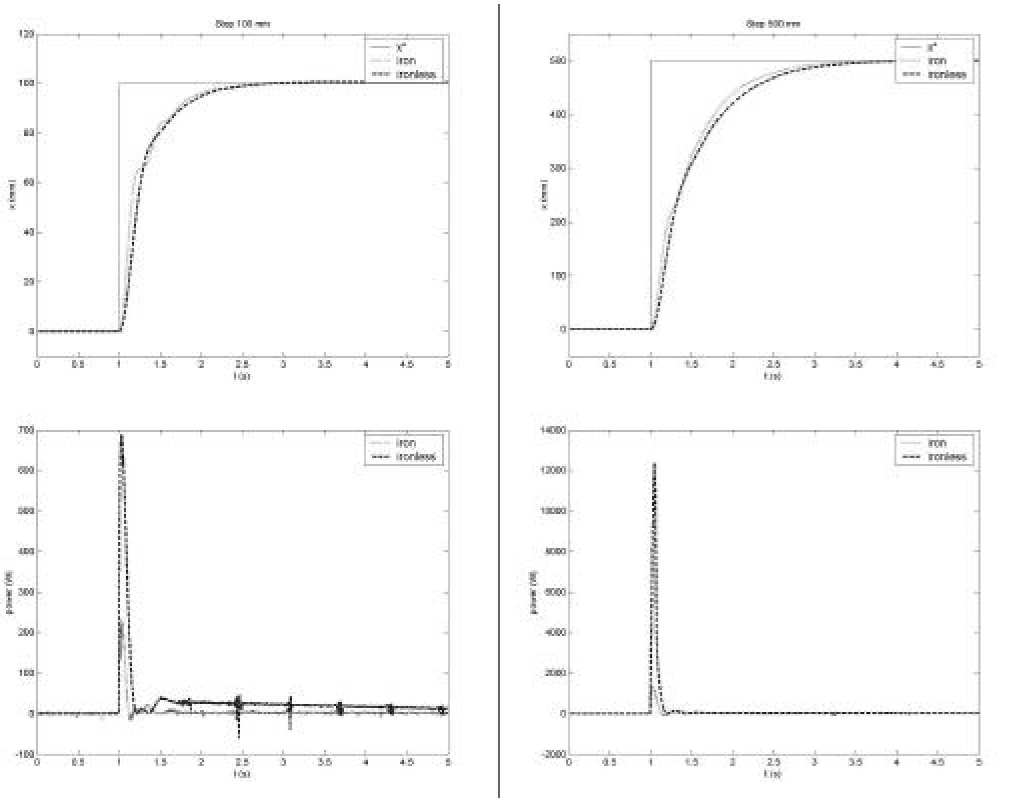


Figure 9. Position response and power consumption with 100 mm and 500 mm step commands

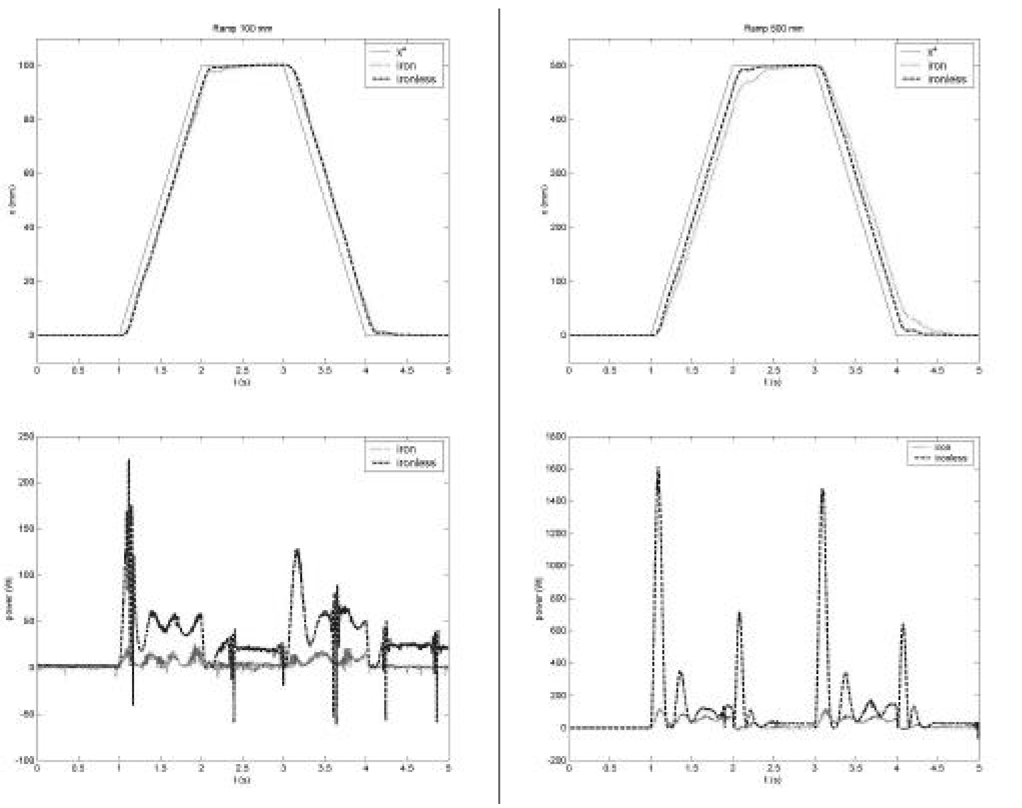


Figure 10. Position response and power consumption with 100 mm and 500 mm trapezoidal commands

A position ramp command corresponds to a constant velocity command. From the figures it can be observed that the position responses have delays of 0.09 ~ 0.13 s (100 mm command) and 0.15 ~ 0.25 s (500 mm command). These are the times that both machines take to reach 100 mm/s and 500 mm/s, on response to the respective speed commands (section 4.2). Non-linearities in the response are more significant in the iron cored PMLSM, as seen in previous figures.

5 Conclusions

Two different prototypes of Permanent Magnet Linear Synchronous Machines were tested to highlight and compare their main electromagnetic characteristics. The only difference between them is the material of their primary core. The same control scheme and power system was used with both prototypes. Table 3 summarises the electromagnetic performance of the two PMLSMs.

Table 3

	PMLSM with iron	PMLSM ironless
Inertia	moderate	low
Detent Force	high	very low
Efficiency	moderate	low
Electrical time constant	low	very low
Thrust	high	high
Attractive forces	high	Low
Costs	high	high

- Both types of machines can achieve similar thrust and acceleration features with sufficient current supply. From the 500 mm/s step command speed test results, we can obtain the thrust and acceleration values shown in Table 4.
- Iron core armature PMLSMs have a good electromagnetic efficiency. They are specially suitable for applications with high accelerations and high levels of thrust, such as servodrives. However, they present the problem of detent force in positioning and also high attractive forces between the primary and the secondary. These forces affect the precision in positioning. Detent forces produce non-linearities in the speed response and tracking errors. There are two ways to avoid this problem. The first is to optimise the constructive design, and the second is to balance the negative effects of these forces by a suitable control algorithm [1][4]. The best solution is to combine both means of actuation. The constructive design of the prototype with iron armature has been optimised in order to reduce the cogging force. Peak values of 4.9 N were achieved.

Table 4

	PMLSM with iron	PMLSM ironless
Time	0.165 s	0.245 s
Acceleration average	3.03 m/s^2	2.05 m/s^2
Thrust average	45.3 N	23.12 N
Id peak	2.52 A	7.62 A

- In iron cored PMLSMs, since power and current consumption are relatively low, repetitive tasks can be performed for long periods of time without overheating problems, and the windings do not need a large section. To achieve improved precision in positioning it is necessary to optimise constructive design and employ a more sophisticated control algorithm that compensates the effects of the detent force.
- Ironless armature PMLSMs (also called moving coil PMLSMs) do not suffer from cogging forces, and are very good drives for accurate positioning. They do not present a net attractive force and therefore they do not have the same mechanical problems with the guides as the PMLSMs with iron on both sides. However they have lower efficiency in electromagnetic power conversion than the iron core armature PMLSMs. They need a higher level of current to produce the same level of thrust, so power consumption is much more significant. The results of the performed tests reveal that ironless PMLSMs need a 400 % higher power supply to achieve the same thrust as the iron cored PMLSMs.
- The higher currents make it necessary to employ windings with a large section to avoid overheating problems. These machines are not suitable for repetitive tasks over long periods of

time if the required loads and dynamics are exigent. Whilst expensive, one option to improve the magnetic circuit would be the use of two rows of magnets at both sides of the moving coil.

- In order to compare two machines exactly with the same geometrical parameters, the windings of the ironless PMLSM were placed at the same distance from the permanent magnets as in the iron cored PMLSM. To increase the electromagnetic efficiency of the ironless prototype, the windings could be brought nearer the magnets to reduce the airgap and improve dynamic performance using the same power supply as in the former case.

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