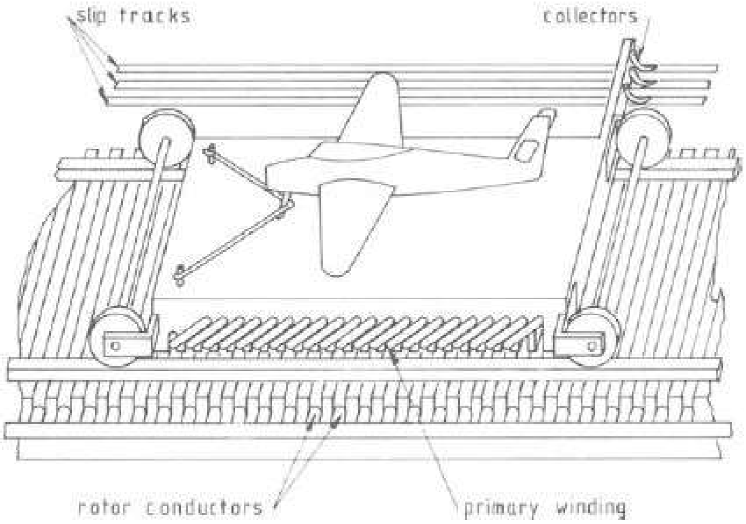
Chapter 1

Introduction

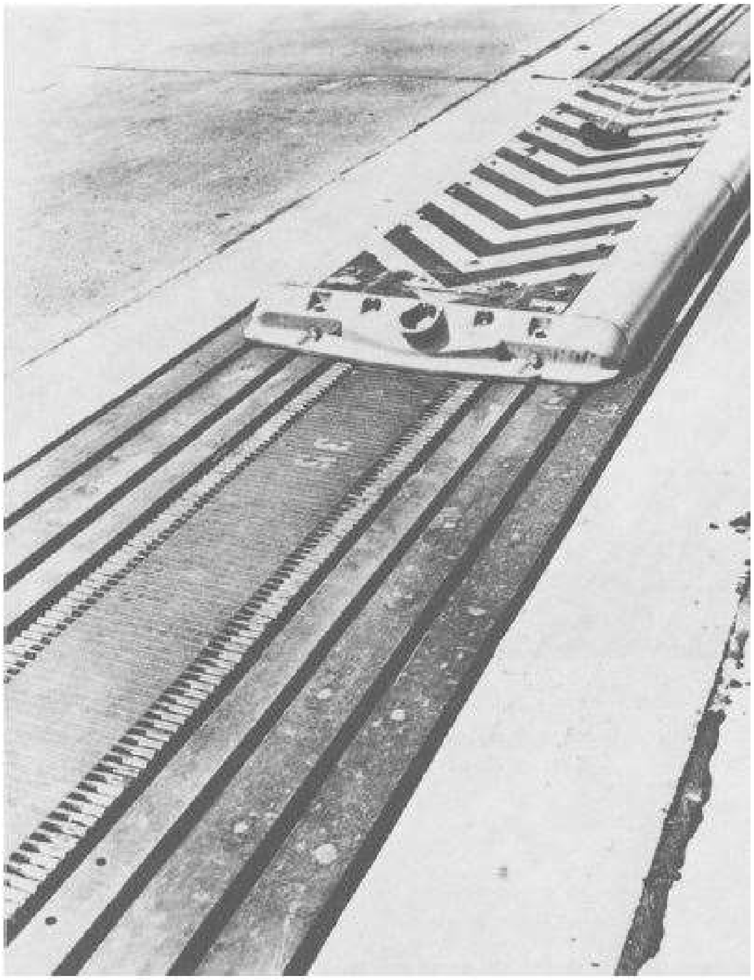
1.1 The Background

The original 1905 version of Linear Induction Motor of Westinghouse Corporation of America had long primary Single Sided Linear Induction motor (SLIM) on track and bogie was having short plate secondary of high conductivity material such as Aluminum or Copper backed by Iron. The scheme was to be used for transport application, however due to large cost of Copper winding it was abolished. In such long primary short secondary LIM, the cost of laying stator with Copper windings on track was excessively large, this limited its use in long distance transportation. For shorter lengths of travel and application, the use of such LIMs were deemed to be cost effective. In between 1905 – 1950 many patents came for using Linear Induction Motor for cloth weaving machine - shuttle propulsion. The 1946 version of **Electropult** was having similar SLIM with graded pole pitch for launching of aircraft for USA Navy as shown in Fig. 1.1. These were energy machines requiring pulse of large three phase high voltage power for a small duration of time. In 1956, Prof. Eric Roberts Laithwaite of Imperial College, London suggested the modification of the experiment of Westinghouse Corporation of America so that transportation using flat type of motor would be possible if the truck or train houses short LIM primary and the secondary

Aluminum plate backed by Iron is laid over the entire track. During that era, engineering society knew the technology of on-board generation as well as transferring large power to moving vehicle using Over Head Equipment (OHE). Prof. E. R. Laithwaite initiated his work on LIM in 1947 and between 1957 to 1965 wrote many papers and attempted to sell his many ideas for variety of purposes. By around 1965, it was realized that LIM was a strong candidate for propelling a High Speed Ground Transportation (HSGT)vehicle and a number of experimental developments were initiated [1]. There had been many imperfections in Linear Induction motor, such as entry and exit end effects, transverse edge effect, large $entrefer$ (French word for iron to iron distance), sheet secondary, unbalanced currents even with balanced set of applied 3-phase voltages is applied, etc. This has given a poor research impetus to LIM in developing countries like India, because large finances would be involved with any new transport schemes. The large sized transportation based on LIM and LSM were actively being sought by developed countries like, China, Japan, USSR, UK and USA. In these countries, the active research contributed to the minimization of imperfections in LIM, by compensating primarily the end-effects. In most of the developed countries which experience the vagaries of weather throughout the year, especially snow, the transportation schemes were based on underground multilevel tunnels. In case of LIM based transport schemes, the overall diameter of tunnels is less, which ultimately reduces the initial cost in tunnelling and recurring cost of ventilation and refrigeration of tunnels [2]. Since the LIM transfers motive power to moving vehicle in a non-contact manner both in levitated transport system as well as in wheel on rail system, the essential requirement of heavy weight locomotive is not essential in LIM propelled transportation schemes. Whereas, in conventional wheel on rail/system locomotive system, the thrust exerted by the wheels on rail for an acceleration of 1 Kmphps for 1 tonne vehicle weight is around 3.11 % of its dead weight. This is because of losses in gearing as well as due to static friction “striction” and air drag. Thus, conventional locomotive essentially



(a) Schematic layout of the Westinghouse aircraft propeller with moving primary



(b) The Westinghouse "Electropult" primary on its track

Fig. 1.1 The American aircraft propelling car, "Electropult" requires heavy mass for its traction. If excessive thrust is delivered to the wheels by a locomotive, it results in an undesirable phenomenon called “wheel slip” [3].

The LIM based Energy Machines have actively been considered for electromagnetic launching in domestic and defence areas. The launchers may be put on trucks, trains, ships, sea / river bed, buildings or inside a tunnel for occult launching. Due to difficulties in imparting large thrust to a low mass projectile using wheel rail system, the rotary motors have got limited role in these areas. Even larger thrusts to low mass projectile for launching cannot be easily provided by wheel rail system. Since in LIM the thrust is provided in a non-contact manner, practically excessively large thrust can be provided to a low mass projectile even in restricted length of travel. Often wheel on rail suspension arrangement for maintaining the air clearance between primary and secondary is provided for the mover (secondary) carrying the projectile when the motor is unexcited. These machines operate at extremely high voltage three phase pulse power momentarily for few cycles of the power frequency. This class of machines is known as “Energy Machines”. Some of the applications are electromagnetic propulsion equipment like drones (having lesser capability to self-take off) on truck / occult place, electromagnetic propulsion of aircraft on warship and space propulsion, which are LIM / LSM based. Other applications of energy machines having larger muzzle velocities are coil gun, rail gun, occult propulsion & thrusters used in defence areas. This unique property of LIM has drawn the attention of many defense scientists. The windings in such devices are the heart of the whole device. The present thesis also concerns the design of windings along with the electromagnetic design of SLIM for launching application. The Energy Machines have critical requirements of thrust production, design of electric (winding), magnetic (core and secondary), dielectric (insulation), mechanical support system, thermal stress and EMI/EMC issues. The power conditioning and other related issues with such machines are beyond the scope of present work. Following section deals with the literature survey of Energy Machines.

1.2 Literature Review and the state-of-the-art

Though the existence of and research in LIM is more than a century old, E.R. Laithwaite is credited to have given the impetus to the modern research in LIM. He supervised several theses on LIM in his laboratory at Manchester University, and got his work published in the proceedings of the IEE (London). Since then, he has published related papers in many professional journals, attracting the attention of many engineers to the subject. He analyzed linear induction motors of various configurations and topologies and their associated applications and published them in his 1966 book [4]. The most salient difference between the linear induction motor and the rotary induction motor and of paramount concern is that the moving member of an LIM has a beginning and an end in the direction of travel. The concomitant longitudinal end effects adversely influence the performance of the linear motor. Yamamura [5] and Poloujadoff [6] gave much deliberation on the theoretical aspects of LIM, especially the influence of longitudinal end effects. They emphasized on the theoretical analysis of single and double-sided linear induction motors SLIM/DSLIM. Another notable contribution was made by Nasar and Boldea [7]. The book on LIMs, by Gieras [8], covers all aspects of the subject, including constructional features, applications, electromagnetic effects, and design. Linear induction motors of single-sided, double- sided, and tubular configurations are analyzed in terms of equivalent circuits and their components. A complete equivalent circuit of a linear induction motor with sheet secondary was developed by R.M. Pai and I. Boldea [9]. They derived the steady state performance characteristics of linear induction motors using one-, two-, and three-dimensional analyses, including longitudinal end effects, transverse edge effects, and skin effects in the secondary. Furthermore, they obtained an equivalent circuit of an LIM from the field analysis, where the longitudinal-end effect, transverse-edge effect, and the skin effect are taken into account. In 1988, a study of the causes and consequences of phase imbalance in SLIM was demonstrated by Anthony R.Eastham and J.F.Gieras [10].

In that paper, two methods of evaluating phase imbalance were presented. The first method, which is analytical, is based on an equivalent circuit model. The second approach, which is numerical, uses the finite-element method. The computational results were validated by comparison with test results on a single-sided LIM at Queens University. It was also shown that phase imbalance produces a reduction in both thrust and normal forces, but this effect is likely to be significant only for high-speed LIM's. Reviews of Linear Induction Motor for high-speed transport (HST) systems are found in [11, 12].

Notwithstanding the above mentioned research on the steady state operation of LIM, the concept of electromagnetic launch, which is a transient application of LIM for a very short duration, is a perpetual subject of military research for its formidable advantages over its fuel powered alternative, like the complete control of the acceleration profile, robustness, reliability, damage management, operational availability, reduced manning, etc. E R Laithwaite has mentioned "Electropult" in his book [4] and also in [13]. In [14–19], different types of launchers are described. A comparison of PM type and LIM type launchers has also been made in [19]. For electromagnetic launching applications of projectiles (circular cross section or otherwise) the methods are discussed in the next Sub-section. In present case, the aim can be met using one or more of the following types of electrical machines of special type.

1.2.1 Rail Gun

In 1980, the Application area and the accelerating mechanism were reported by Henry Kolm et al. by establishing MIT National Magnet Laboratory, to study some accelerating mechanisms of interest [20]. A 6 m helical rail launcher, which is a twin-boom device designed to accelerate a 5 kg glider to 100 m/s at 100 G acceleration is shown in Fig.1.2. The principle of operation of railgun is same as the conventional homopolar DC machines in linear form. These are used for high muzzle velocities and comparatively smaller mass of projectile. Extremely enormous power is transferred conductively through a pair of rails, which results in arcing and ablation of projectile and rails as reported in [21–29]. While explosive-powered military guns cannot readily achieve a muzzle velocity of more than 2 km/s, railguns can readily exceed 3 km/s. For a similar projectile, the range of railguns exceeds that of conventional guns. The destructive force of a projectile depends on its kinetic energy and mass at the point of impact. Railguns are still very much at the research stage after decades of R&D, and it remains to be seen whether they will ever be deployed as practical military weapons given the complexity involved in the pulsed power supplies that are needed for electromagnetic launcher systems.

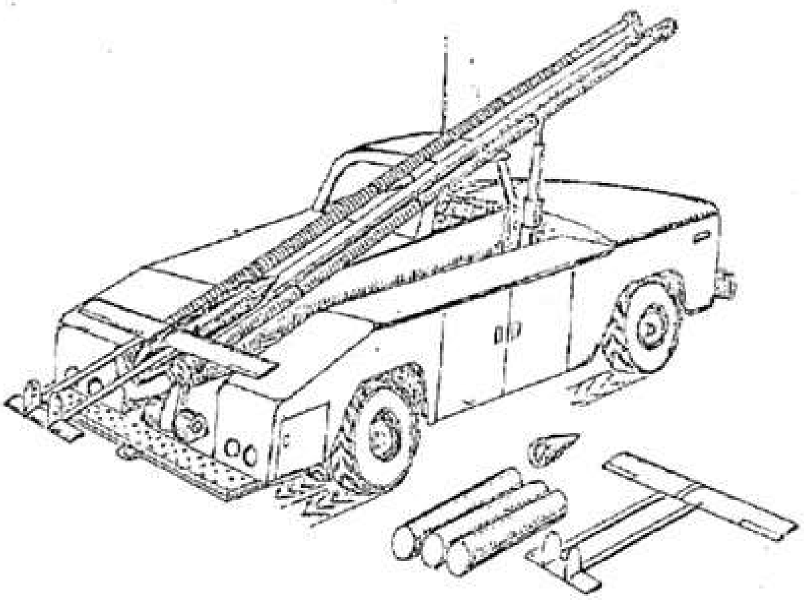


Fig. 1.2 Electromagnetic launcher for fifty-pound cargo and reconnaissance gliders

Source: M.I.T. [22]

1.2.2 Coil Gun or co-axial accelerator

Coil gun works on the principle of reluctance variation. The pulse DC power is required when the ferromagnetic pellet is in the lowest inductance position, the movement of pellet takes place in the direction of rising inductance. The power needs to be cut off when the pellet is under maximum inductance in order to avoid the reverse movement. Coaxial launch technology was introduced by Henry Kolm and Peter Mongeau [30] and the schematic view is shown in Fig.1.3. The thrust of Coaxial launcher is hundred times of railgun thrust owing to contactless propulsion. Often Compulsators (Compensated Pulse Generators) are used for repetitive firing of EM gun [31]. Further research and advancements are found in [14, 25, 29, 30, 32].

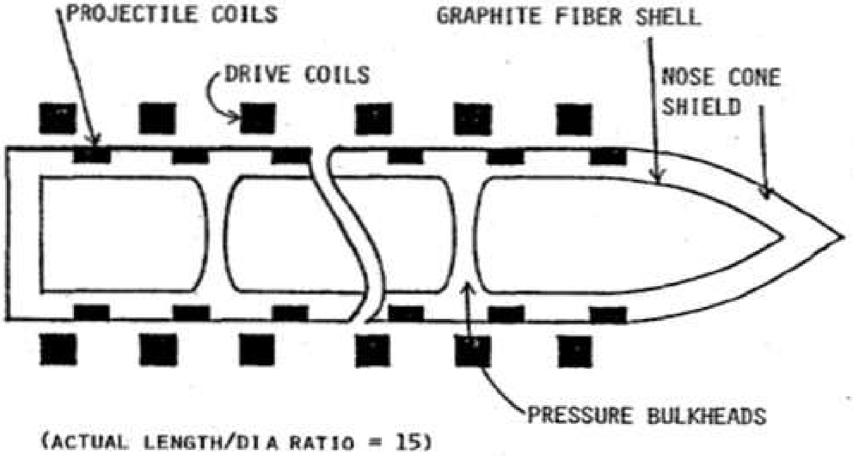


Fig. 1.3 Multiple-coil slender projectile

[30]

1.2.3 LIM/ Tubular LIM/ LSM (or LPM)/ LSRM based Electromagnetic propulsion for heavy systems

While the preceding two subsections briefed on the EM Gun technology for low mass projectiles, EM launch of heavy mass systems rely on machines like LIM operating at comparatively lower velocity for safe launching of mass. Linear Induction Motor (LIM) follows the same principle of rotary induction motor. When the rotary induction motor is hypothetically cut down by an imaginary line along the axis and rolled out, a flat linear induction motor is obtained. In this thesis, flat-type LIM is discussed. Three-phase winding is placed in primary slots. The secondary is generally an aluminum sheet backed with laminated iron. On the basis of length of primary and secondary of the machine, it has two types, namely, long primary, and long secondary [33] as depicted in Figs. 1.4 and 1.5.

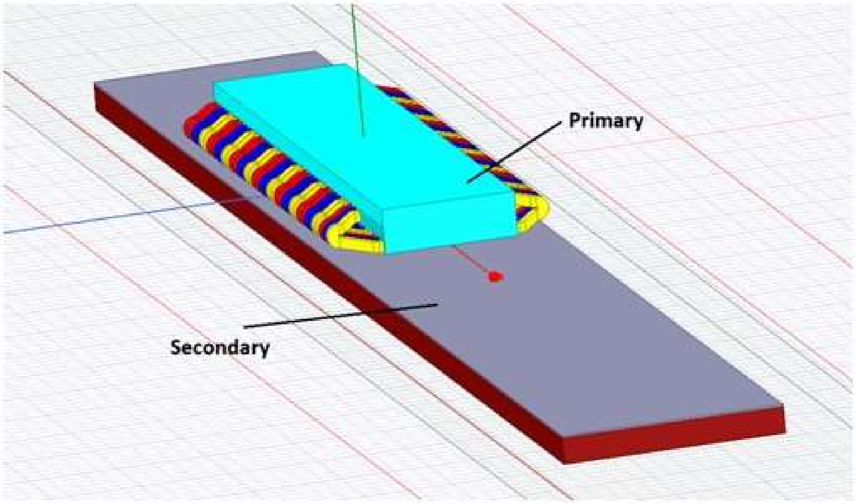


Fig. 1.4 A short primary long Secondary LIM model.

There are two types of topologies used in practical application, one is SLIM (Fig. 1.6) and the other is double-sided LIM (DLIM) (Fig. 1.7).

In comparison with a rotary induction motor, LIM requires a comparatevly larger air gap for limiting normal force. Thus, the magnetizing current drawn by the primary is large, resulting in poor power factor and low efficiency. When a short primary LIM is under operation with the concomitant relative motion between the primary and the secondary, previously unmagnetized portions of the secondary continuously come under the influence of the primary at the leading edge (Entry End) of the machine while previously magnetized secondary material goes out of the influence of the primary at the trailing edge (Exit End). Both these phenomena add exponentially decaying components to the air gap flux traveling at synchronous speed. Thus, the air gap flux is distorted, and this distortion is widely known as "End Effects" in literature. For a low speed motor, the end effect

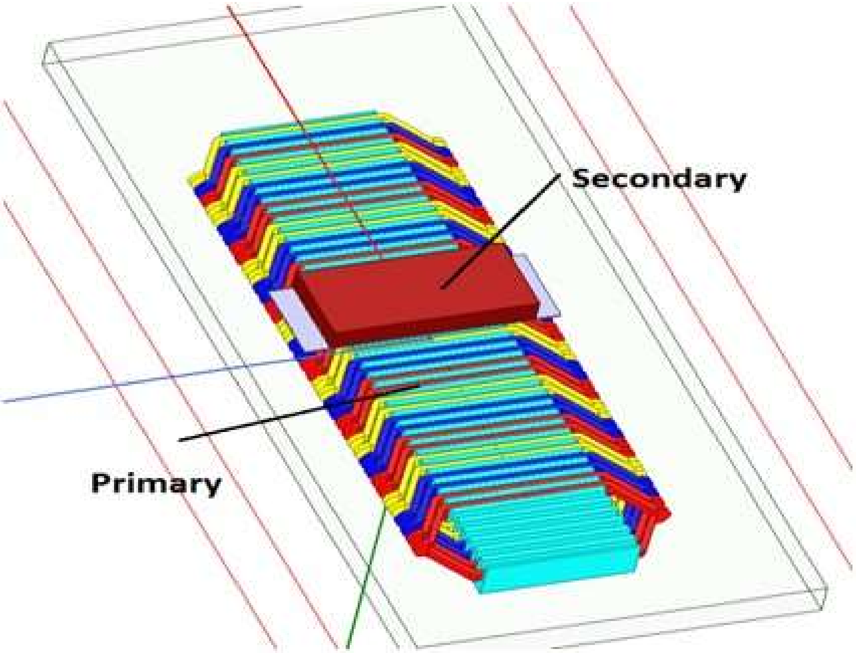


Fig. 1.5 A long primary short secondary LIM model.

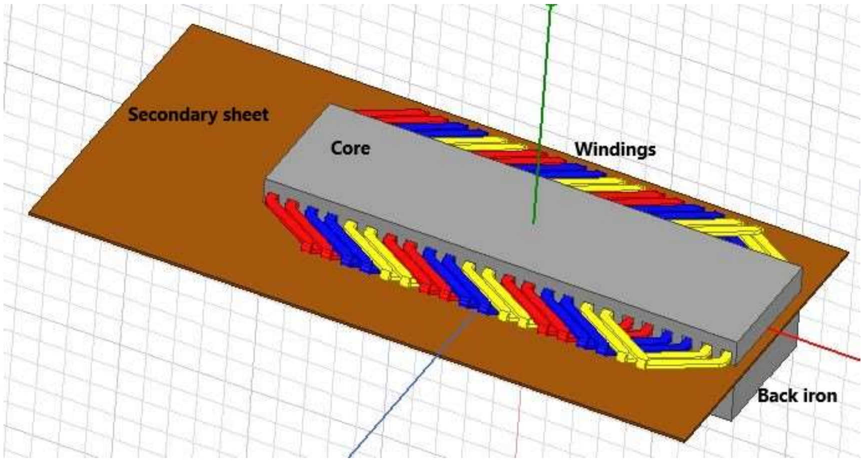


Fig. 1.6 An SLIM model with short primary long secondary.

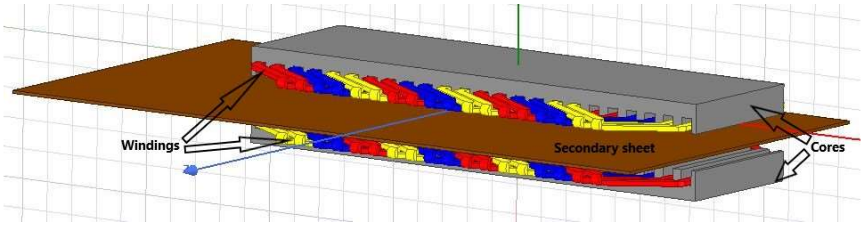


Fig. 1.7 A DLIM model with short primary long secondary.

reduces the thrust in high slip region, while it increases the thrust in low slip region near the synchronous speed. In fact, there exists a small positive thrust even at the synchronous speed [5]. In contrast, for a high speed motor, the end effect does not change the thrust in high slip region, and it makes the thrust curve undulate in the middle slip region, and reduces the thrust considerably in the low slip region. High speed motors can exhibit negative thrust generation at synchronous speed. An LIM can achieve good performance in-spite of large air-gaps, had it not been for the end effects. The end effects degrade the superior performance of a high speed linear induction motor.

The criterion for separating low-speed linear induction motors and high-speed linear induction motors is given by the following inequality:

$$\frac{\mu_0 \, v^2}{4 \, \omega \, \rho_s \, g} >> 1 \tag{1.1}$$

where v is the linear velocity of the motor(m/s), ω is the supply frequency in rad/s, ρ_s is the surface resistivity of the secondary sheet and g is the air gap. The above given inequality is for high-speed LIM. For low-speed motors the below formula holds:

$$\frac{\mu_0 \, v^2}{4 \, \omega \, \rho_s \, g} < 1 \tag{1.2}$$

Generally, for energy machine applications, LIM topology of longer primary (stationary) and shorter secondary (mover) is adopted to allow high current to flow in the stator for a very short duration. Thus, high magnitude current collection issue is averted. Analysis and design of such LIMs are discussed later. NASA tests a linear motor on a prototype Maglev railroad, 1999 [34]. Tracks like this could be used to launch vehicles into space in future (Fig. 1.8). A typical shuttle to which an on-board aircraft is towed is depicted in Fig. 1.9. It was not until the recent technical advances in the areas of pulsed power, power conditioning, energy storage devices, and controls gave credence to a field-able

Fig. 1.8 Magnetic launch assist.

Fig. 1.9 An on-board fighter aircraft with the shuttle in the inset.

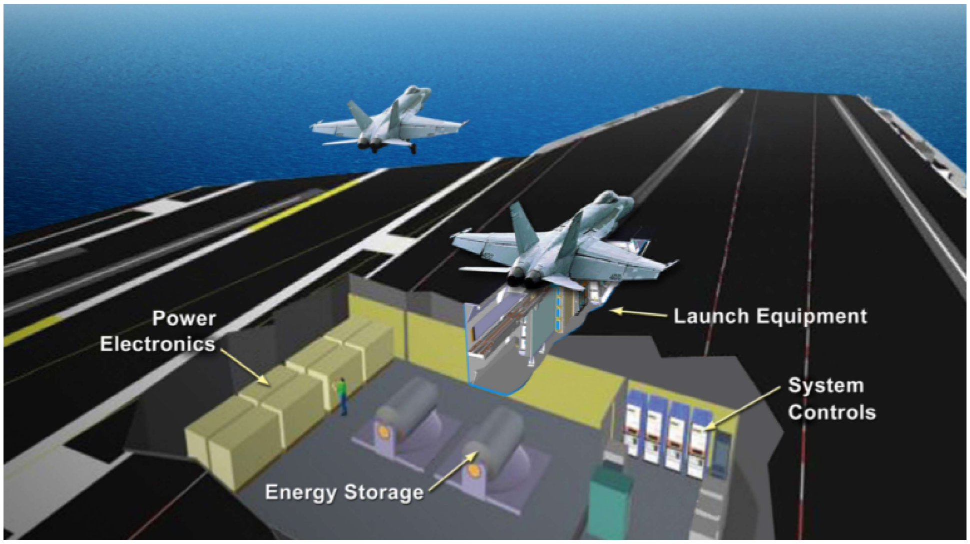
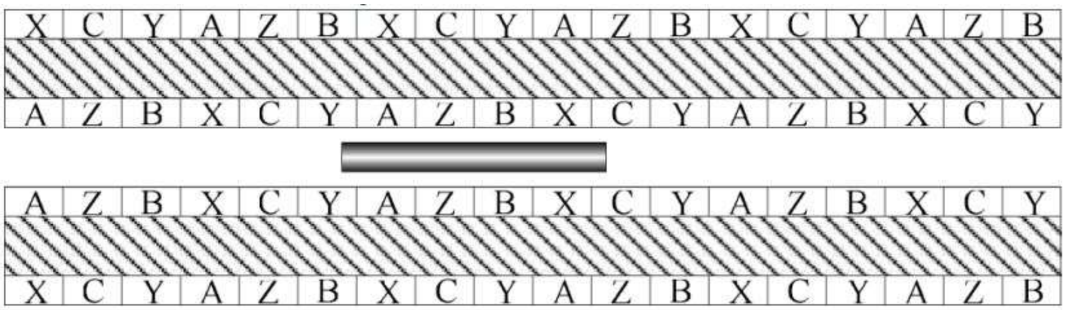


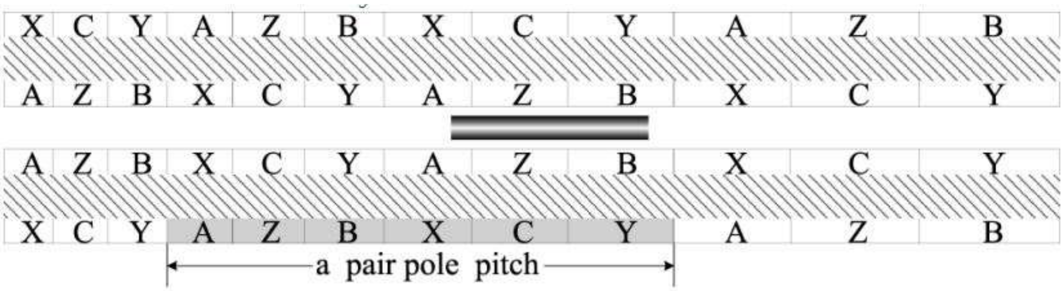
Fig. 1.10 Fully integrated electromagnetic launch system.

electromagnetic aircraft launch system [35]. It consists of four main elements, which are power source subsystem, power conditioning subsystem, launch motor subsystem, and closed-loop control subsystem. The power source subsystem stores energy from power station and provides pulse power to the power conditioning subsystem in a short period, then the power conditioning subsystem converts the power into a variant-frequency variant-voltage power, and releases it to the launch motor through block feeding method [36]. It is intended to be a fully integrated electromagnetic launch system [37], including energy storage, power electronics, launch motor and control subsystems. The intent is to evolve the component technologies throughout the expected fifty-year life of carriers. The concept is illustrated in Fig. 1.10.

Under constant voltage consatant frequency operation, an LIM may overspeed beyond its synchronous speed, causing a speed oscillation near synchronous speed. In order to have uniform acceleration, a Variable Pole Pitch Linear Induction Motor (VPPLIM) for Electromagnetic Aircraft Launch System was proposed in 2015 [38] as depicted in Fig. 1.11. VPPLIM was designed in a special way such that it reduced the power electronics devices involved allowing for constant voltage and constant frequency supply. However,



(a) Constant pole pitch structure



(b) Variable pole pitch structure

Fig. 1.11 Constant and variable pole pitch LIM structures

maintaining inventory for the purpose of replacement of a faulty stator segment of a VPPLIM is costlier.

1.2.4 Linear Synchronous (Permanent Magnet) motors

Operational impacts of electromagnetic launch of aircrafts from the carrier ships and the compatibility issues were addressed for the first time in 1995 [35]. A preliminary design study with linear synchronous motor (Fig. 1.12) as an electrical catapult for launching a 300 kg unmanned air vehicle (UAV) to an exit velocity of 50 m/s with constant acceleration over a distance of 14 m along a slope of about 30^o was done by developing a fast numerical code on computer [39].

During this era numerous simulation based studies were carried out to evaluate alternative design concepts and their feasibility and comparative strengths. In 2005, one such effort reported the Design and Simulation of a Permanent-Magnet Electromagnetic

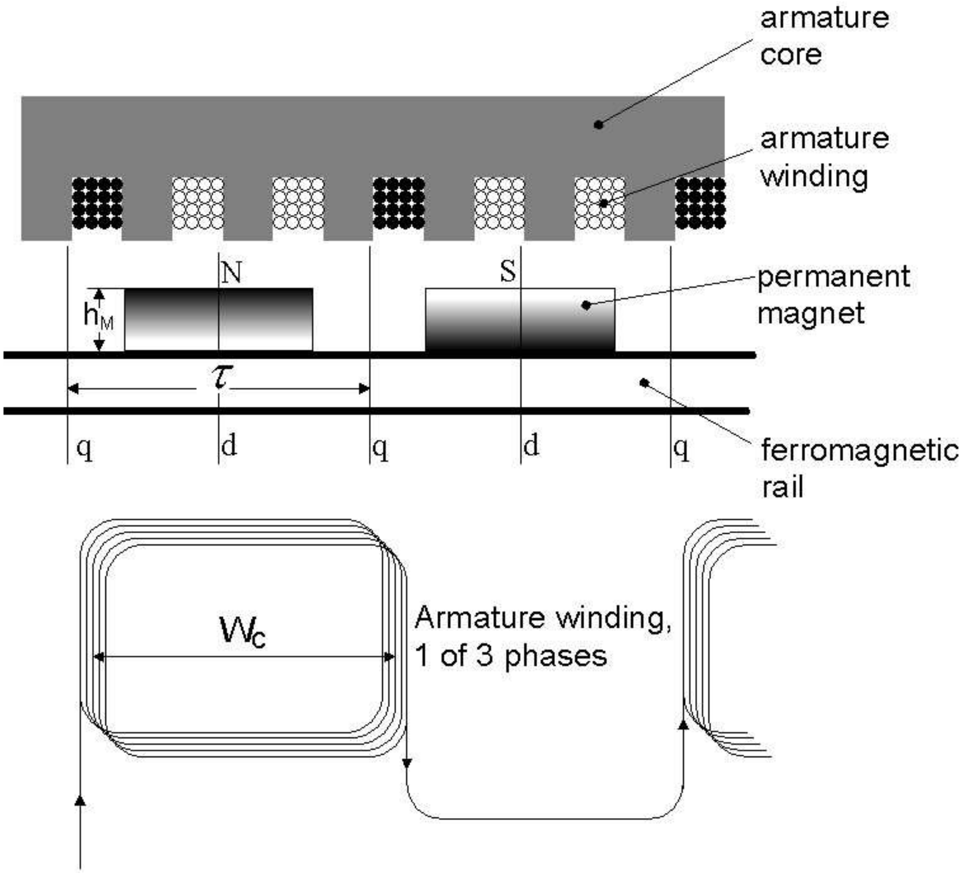


Fig. 1.12 LSM with surface PMs and three-phase armature winding.

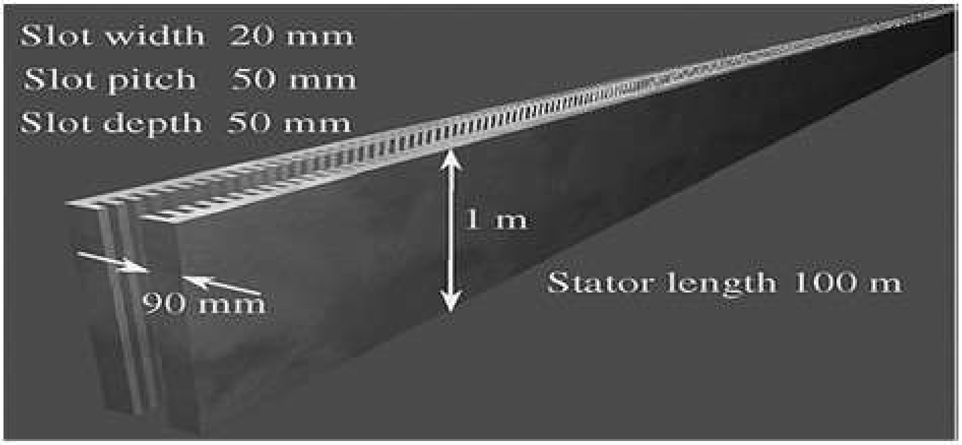


Fig. 1.13 Stator dimensions

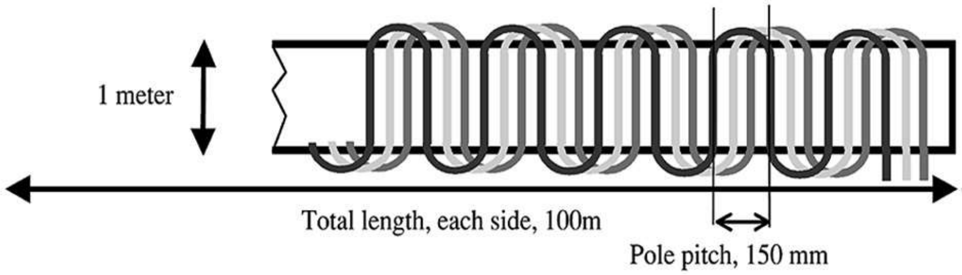


Fig. 1.14 Three-phase one-slot-per-pole-per-phase stator winding structure

Aircraft Launcher [15]. Maximum speed of 100 m/s was obtained in 100 m travel with 1.3 MN maximum thrust . The DSLSM stator is shown in Fig. 1.13 and its three phase windings are shown in Fig. 1.14.

1.2.5 Effects of Joints in Reaction Rail on the Thrust of LIM

Linear induction motor has been in use in a variety of applications like factory automation and transportation. LIM is considered as a linear counterpart of screened rotor induction motor [40]. Its operation is based on the induction of eddy currents in conducting rail, acting as a secondary or reaction rail. Although, different types of secondaries such as squirrel cage [41], ladder-slit [42], plain sheet and ferromagnetic rail [43], [44] have been proposed in past, but composite sheet secondary gives a better alternative due to its low cost [45], [46]. In case of squirrel cage type of secondary the presence of ferromagnetic and conducting material alternatively results in a better force production, notwithstanding this, the preparation of a long squirrel cage type secondary is not always feasible. In case of composite sheet secondary, a continuous conducting sheet or a continuous back-iron is not ensured unless proper electrical continuities of the respective materials are maintained throughout the path of travel. The preparation of reaction rail is done with joining longitudinal pieces of sheets of conducting material and that of ferromagnetic material both of proper sizes and shapes. The prepared reaction rail may offer electrical discontinuities due to improper joints at certain regular distances. Such a discontinuity abruptly breaks the path of the induced eddy currents and thereby momentarily generating thrust ripples at the instant when LIM primary moves over it leading to vibrations. Such operational difficulties of LIM have been reported in [47], [48]. These joints in reaction rail are having comparatively greater significance under dynamic condition as compared to standstill condition.

Some recent works have analyzed the air-gap flux density and eddy current distribution for the investigation of thrust and efficiency for LIMs having large discontinuity in reaction rail (uncoupled region) [49] and determination of equivalent circuit for LIMs with laterally asymmetric secondary [50].

1.3 Motivation

A rapidly growing trend in engineering is the 'do it at any cost' fashion. As our ambitions grow in engineering ventures, the demands on ingenuity become greater and the more powerful question becomes 'Can it be done at all?' than 'How efficiently can it be done?' Greater than the cost of the instruments required in sending a man into space is the question of their reliability [4]. It is with this question in mind that the linear induction machines have been chosen for electromagnetic propulsion application, bearing in mind their advantages of low cost, robustness and ability to generate large starting forces within a short period of time and shorten length of travel. There was a time when these machines were treated as "special" machines, but today, LIM has become the heart and soul of the modern transportation and propulsion systems.

1.4 Research objective

In view of the above motivation, the objectives of this thesis are as follows:

- Analysis of motion of the projectile by mathematical modeling.

- Analysis of speed thrust characteristics and design of LIM for moving a mass of specific weight for a specific distance to reach certain specific velocity.
- Performance analysis analytically using Parseval's method of Fourier Transform for constant current drive
- Performance analysis using Finite element method (Ansys Maxwell) for different designs of LIM.
- Design and Procedure for development of possible scaled experimental setup for testing and assessment of LIM performance.
- Comparing performance of LIM by different methods.
- The study of problems associated with launching application viz. mover oscillating around super synchronous speed.
- Investigation of effects of Joints in reaction rail and back-iron and proximity of ferromagnetic material on the thrust of LIM.

1.5 Thesis outline

The subject matter of the thesis is organized in the following chapters:

Chapter 1 deals with the Literature Survey and the Plan for the Work. Chapter 2 deals with the Energy Machines, Joules Limit Criterion and the role of windings in LIM operated Energy Machines. Chapter 3 concerns with the Design of SLIM for Electromagnetic Launch under Constant current excitation. And it is found that German Silver is the most suitable candidate. The FEM, analytical and experimental results for different frequencies at standstill condition have been reported. Chapter 4 deals with the evaluation of different types of windings of SLIM for EM Launch under Constant Voltage excitation. Chapter 5 deals with the effects of joints in the reaction rail on the thrust of SLIM.

Finally, Chapter 6 concludes the present thesis with a discussion of its implications and future prospects.

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