Linear Electric Motors for Aerospace Launch Assist

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Abstract

This paper summarizes the results of a design study investigating the use of linear electric motors in an aerospace electromagnetic launcher application requiring 7g's of horizontal acceleration to a velocity of 300m/s. The study initially reviews the current state of high-speed electric machines in applications similar to the one proposed. Induction and synchronous linear motors are then evaluated for suitability to the application by analyzing their characteristics in this high-speed operating regime. A detailed design approach is used to synthesize machines capable of meeting the launcher's performance requirements, since the conditions fall outside of the conventional design envelope. Realistic physical features of all electrical power system components are included to ensure the evaluated systems are physically realizable. The two motor types are compared for suitability to the application based on performance, cost, and system integration issues. Finally, a prototype demonstrator design is proposed to verify the results of the study.

1 Background and Motivation

This study into the use of induction and synchronous linear motors for an aerospace launch assist application was performed in support of NASA's Reusable Launch Vehicle initiatives. NASA has a goal of reducing the cost of launching cargo into space by one or two orders of magnitude within 25 years. One means of achieving this goal is to develop a more cost efficient method of accelerating the craft than the current two-stage rocket engine system.

NASA is pursuing an electric powered launch assist scheme that accelerates the craft horizontally along the ground (using a power source external to the vehicle), thereby eliminating one stage of rockets. This approach of replacing the first rocket stage with an electric launcher track could reduce the per-launch cost and improve safety and reliability.

This study for NASA focused on investigating the high-speed use of conventional, continuous linear motors (induction and synchronous) to accelerate launch craft in numerous scales. NASA intends to begin with a 45 kg demonstration, and increment the scale of prototypes to ultimately apply this technology to a full size launch craft. Masses of 45, 455, 4550, 45500, and 455,000 kg were considered in this work.

2 High Speed Linear Motor Review

As a first step in evaluating the use of linear motors in a launch assist scheme, a literature review was undertaken to investigate whether electric machines are currently in operation in related applications with similar requirements.

The major uses of continuous linear motors found in the literature review were ground transportation (high speed rail and amusement rides), machining operations, materials transport / handling, and other launcher systems under development [1]-[11]. The highest speeds encountered in these results were MagLev trains tested at 153 m/s [12]. This is significantly lower than the NASA requirement of 300 m/s.

Very high speeds have been achieved with pulsed linear motors used as accelerators and rail guns. Velocities well above 5 km/s have been demonstrated [13]. However, these machines are not well suited to launch assist due to implementation difficulties in long lengths. Nevertheless this fact serves as a data point for velocities achievable with electric machines.

Figure 2.1 summarizes the demonstrated speed ranges of electric machines in numerous high-speed applications. From this chart it is apparent that there are no known high-power applications demanding 300 m/s operation from a linear electric motor.

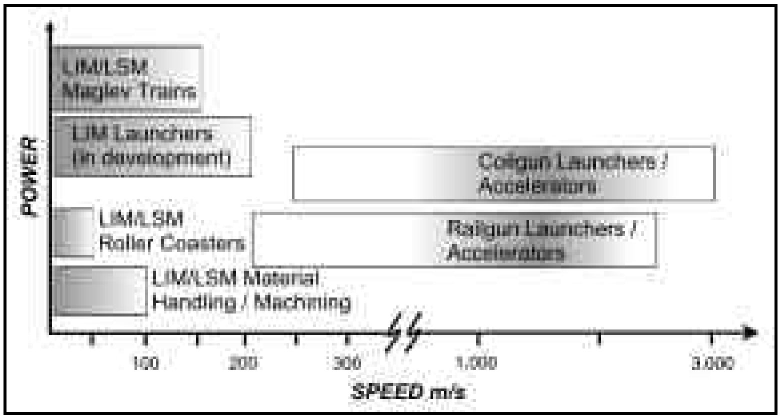

Figure 2.1 Speed range of linear electric motors

Given the apparent "gap" in applications in the area of 300 m/s, no currently existing machinery can be identified as suitable and proven for the launch assist application under study. With this is mind, it is very likely that one of the existing classes of machines will need to have its operating range extended to accommodate the launch assist conditions. At this point it is unclear whether it will be better to advance continuous motors (induction and synchronous) beyond their existing ranges to higher speeds, or to refine pulsed machines for lower speed, lower acceleration, continuous operation over long distances.

3 Launcher Mechanical Requirements

As an initial estimate of the scale and capabilities of linear motors that would be necessary to meet the requirements of the study, preliminary calculations were performed. The NASA specifications require constant acceleration of the craft from rest to 300 m/s at 7g's. These specifications were expanded into size and parameter estimates by applying them to a mechanical system and computing the approximate levels of force, power, consumed energy, and other factors.

Table 3.1 Mechanical requirements of launchers

Launch Parameter	units	45kg	455kg	4550kg	45500kg	455000kg
Frontal area (*input*)	m^2	0.25	1.16	5.38	25	116
Constant acceleration (*input*)	m/s^2	7	7	7	7	7
Launch velocity (*input*)	m/s	300	300	300	300	300
Time to launch	s	4.62	4.62	4.62	4.62	4.62
Launch distance	m	656	656	656	656	656
Constant inertial force	kN	3.09	31.2	312	3,125	31,245
Drag force at launch	kN	7.40	34.3	159	740	3,433
Total force at launch	kN	10.49	65.6	472	3,864	34,678
Delivered inertial energy	MJ	2.03	20.5	205	2,048	20,478
Drag loss energy	MJ	1.71	7.9	37	171	792
Total expended energy	MJ	3.73	28.4	242	2,219	21,270
Peak inertial power at launch	MW	0.93	9.4	93.7	937.4	9,374
Peak drag power at launch	MW	2.22	10.3	47.8	222	1,030
Total peak power at launch	MW	3.15	19.7	142	1,159	10,404

A kinematic model was created to compute the dynamic mechanical loads including inertial forces and aerodynamic drag (substantial in this application) encountered at all speeds throughout the launch. With this model, a speed profile is imposed and the non-linear drag forces are computed over the entire speed range, and the resulting energy loss and power requirements quantified. The results of these mechanical load estimations for all craft sizes can be seen in Table 3.1. In reviewing the results for the 45 kg craft, it is apparent that the high drag force has a substantial impact on the peak required power as the drag loads exceed the 7g's acceleration load.

4 Detailed Analysis of Linear Motors

Induction and synchronous linear motor technologies are at mature levels, however in this case, each type would need to be pushed beyond the existing design envelope to meet the application requirements [14]-[16]. Only through the process of synthesizing and simulating each motor for these conditions can it become clear if the necessary materials and operating characteristics can be realized.

To this end, a design study is performed for both induction and synchronous linear motors in this operating regime. Both types are analyzed in detail with their parameters iterated and optimized, and a preliminary design of each is simulated to evaluate the operation under these high force, high frequency, high current conditions.

4.1 Linear Induction Motor Design

The general configuration assumed for the launcher induction motor concept is a long, double-sided stator that sandwiches a moving secondary conductor sheet. The stator is fixed to the ground and takes on the form of a track. The moving secondary is a continuous sheet of conductor material that attaches to a carrier mechanism to drive the craft. A schematic of this configuration can be seen in Figure 4.1.

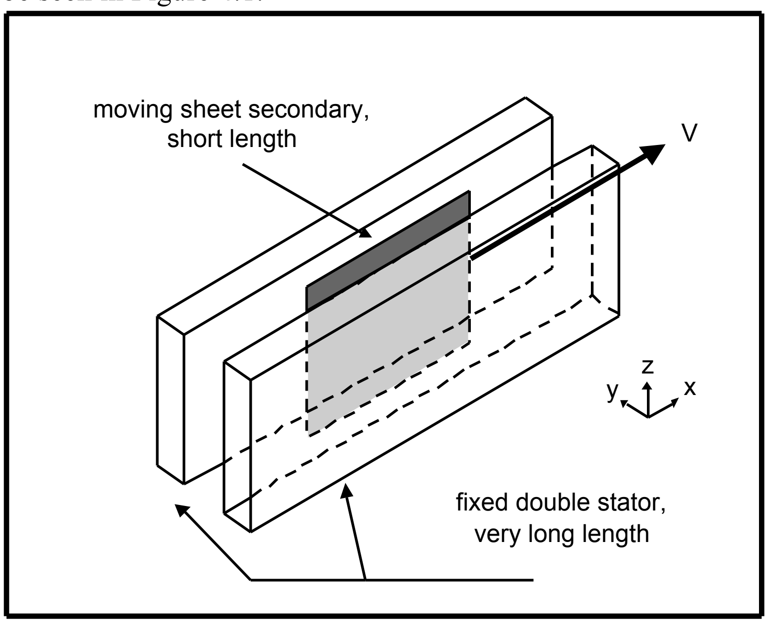

Figure 4.1 Linear induction motor configuration

Because of the long length of motor required for this application, only a small fraction of the stator is being used at one time. For this reason, the stator of this induction machine is assumed as divided into separate segments. This "block switching" allows short portions of the stator to be energized two-at-a-time in succession, to avoid resistance losses in the long unused portions. The length of an individual portion, and total number of portions is a parameter that is determined through trade studies.
To solve for baseline values defining the general size of the induction motor, an electromagnetic code was written. This "continuum model" is a closed-form field solution of the electromechanics of the linear induction motor that evaluates the critical electrical and physical parameters of a design.

The inputs to the code specify the induction machine geometry and material properties. The routine then applies inverse-dynamics to solve for the operating conditions necessary to complete the prescribed acceleration of the mechanical load from 0 to 300 m/s including the aerodynamic drag forces. The outputs are the critical electrical and thermal parameters of the system that determine whether the design can be physically realized. The geometry parameters of the linear induction motor are shown in Figure 4.2.

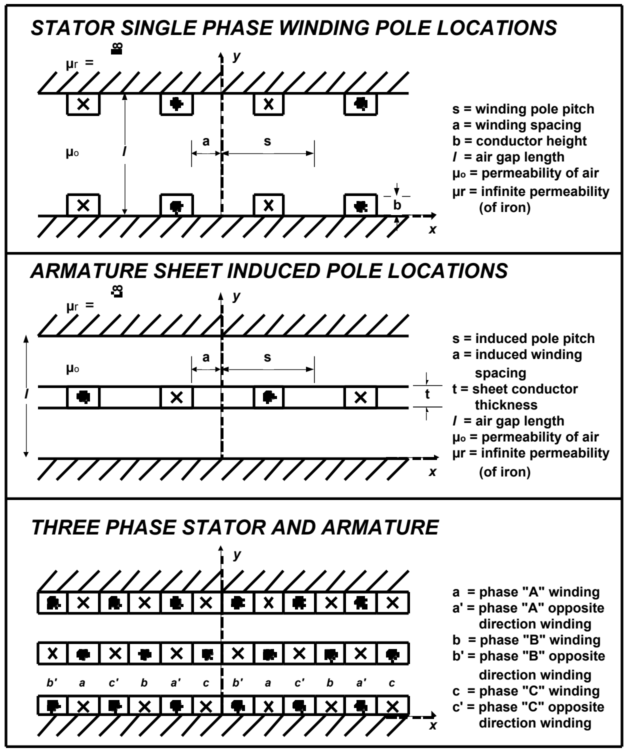

Figure 4.2 Induction motor geometry parameters

The operation of the closed form field solution model proceeds as follows. The algorithm steps through increments of velocity to represent the imposed constant acceleration of the payload and secondary. At each speed increment, the vector control law determines the necessary applied stator frequency to establish the required force, without exceeding the limit of maximum flux density. In each of these computations, the effects of the harmonic current interactions are considered, including power loss and drag forces resulting from negative sequence harmonics. The computed values of fundamental current density, slip, power loss, secondary temperature rise and total force are recorded for post analysis. The values include mechanical, electrical, and thermal parameters as follows:

- v — the velocity profile of the secondary and payload
- F_t — the total force applied by the secondary to overcome inertia and losses
- F_d — the internal drag forces of the machine throughout acceleration
- F_{net} — the net force exerted on the mass (controlled to be constant for constant acceleration)
- A_{kz} — harmonic components of stator current density
- s — slip: the relative speed between the traveling flux wave and the secondary sheet
- P_{loss} — the power loss due to internal drag forces
- dT — the temperature rise of the secondary due to power loss heating
- n_i — the stator ampere-turns required to generate the magnetic field
- B_y — the stator flux density (controlled to be constant)

The continuum model was employed to choose optimized parameters of an induction motor suitable for driving the 455 kg mass craft. Table 4.1 summarizes the final values selected through the design study trades. Table 4.2 indicates the performance parameters of this design.

Table 4.1 LIM baseline geometry configuration

Stator	
Pole pitch	0.3 m
Active height	0.3 m
B max	1.25 T
Electrical frequency (max)	500 Hz
Secondary	
Length	3.0 m
Active height	0.3 m
End turn overhang	0.15 m (per side)
Material	Aluminum
Mass	78 kg
Total air gap	36 mm

Table 4.2 LIM field solution baseline performance

Quantities	
Velocity	300 m/s
Constant acceleration level	7 g's
Maximum generated force	73222 N
Total energy consumed	34.0 MJ
Maximum power level	21.8 MW
Electrical power efficiency	96.6%
Max line current density	221 kA/m
Slip (relative speed)	0.35 m/s
Max ampere-turns	28.2 kA-t
Secondary temp. rise	56.3°C

Numerous stator winding schemes and patterns could be used to generate the stator flux distribution imposed in the field solution—it is winding independent. However, to quantify how the LIM interacts with its power supply, stator winding parameters were selected and the resulting impedances calculated. The winding configuration was chosen through optimization; results are shown in Table 4.3. A full electrical power system and mechanical load dynamic simulation was performed using these parameters.

Table 4.3 LIM electrical parameters

Stator Winding Configuration	
Number of turns per coil	3
Coils per segment	10
Segment uncovered length	10 poles
Stator conductor cs area	0.0012m^2
EQ Circuit Parameters	
Rs	0.0034 Ohm
Ls	41 uH
Lm	78 uH
Rr	5.4e-4 Ohm
Lr	1.38 uH

4.2 Linear Synchronous Motor Design

The general configuration assumed for the launcher synchronous motor concept is essentially identical to the induction machine, with the exception of the armature. The moving secondary armature of the synchronous machine must contain persistent magnetic field poles. These poles could be established by many different devices, but for the purposes of this study, a particular type is not chosen. The poles are simply imposed mathematically. In actual implementation, conventional DC windings, superconductors, or permanent magnets could be employed.

The stator of the synchronous motor concept is a long, double-sided stator that sandwiches the moving secondary armature. The stator is fixed to the ground and takes on the form of a track. The moving secondary establishes a permanent magnetic field and attaches to a carrier mechanism to drive the craft. A schematic of this configuration can be seen in Figure 4.3.

Wherever possible, the approach used to configure and design the synchronous motor is essentially the same as for the induction motor, except where differences must naturally exist. This allows the baseline machines to be as similar as possible, so they are easily compared. Additionally, the simulation architecture and codes were recycled to a large degree.

As the secondary current is controlled rather than induced in the synchronous machine, the selection of its geometry parameters is less complex than for the induction motor. A field solution code is not required, instead an equivalent persistent current can be explicitly solved to generate the required force for a given stator flux distribution.

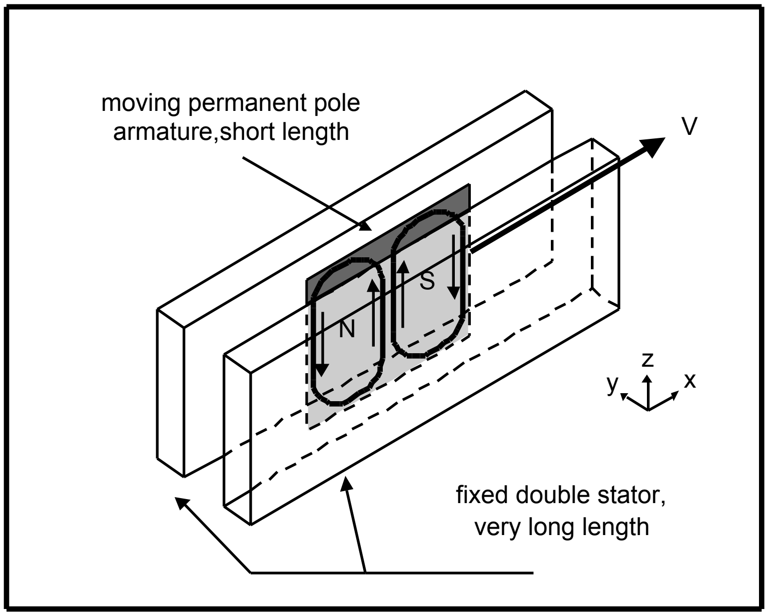

Figure 4.3 Linear synchronous motor configuration

The synchronous motor baseline design was developed to meet the force and high-speed requirements of this application for the 455 kg craft case. The parameters of the baseline synchronous machine geometry are listed in Table 4.4. The baseline stator winding configuration for the synchronous motor and its inductance and resistance parameters are shown in the Table 4.5.

Table 4.4 LSM baseline geometry configuration

Stator	
Pole pitch	0.3 m
Active height	0.3 m
B max	1.25 T
Electrical frequency (max)	500 Hz (max)
Armature	
Length	3m,10 pole pitch
Active height	0.3 m
End turn overhang	0.15 m (per side)
Mass	78 kg
Total air gap	36 mm
Equivalent persistent current	57 kA

Table 4.5 LSM computed electrical parameters

Stator Winding Configuration	
Number of turns per coil	3
Number of coils per segment	10
Segment uncovered length	10 poles
Stator conductor cs area	0.0012 m^2
Stator Electrical Parameters	
Phase self inductance	0.4788 mH
Phase to phase mutual ind.	-0.18819 mH
Phase resistance	7.8 m Ohm

5 Launch Power System Dynamic Simulation

To evaluate linear motors for the launcher application, the combined electro-mechanical system was dynamically simulated through a launch to verify its performance. For this, all components of the electric power supply system had to be represented with sufficient realism and fidelity. This need stems from the fact that the power system interacts dynamically with the motor and the load, and that the physical limits of the power supply impose operational limits on the motor, and therefore the overall system performance. The design of a motor is therefore substantially dependent on the characteristics of its power supply, as well as its load. For this reason, the major components of the launcher power system must be appropriately characterized. For this study, no components were completely idealized.

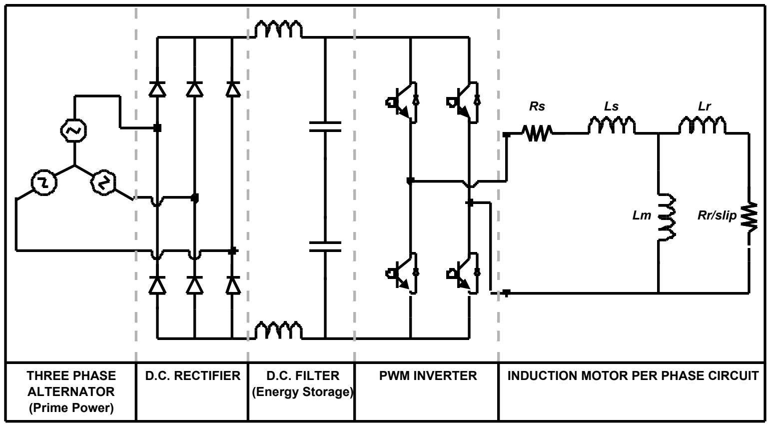

Figure 5.1 Simulated power system schematic

Figure 5.1 schematically represents the assumed major power system components of the 455 kg craft launcher system for both motor types, shown supplying a single phase of a multiphase induction motor. With the exception of the motor component, the power system schematic is identical for supply of a synchronous motor.

As seen in the figure, the major components are the alternator, the DC rectifier, the DC filter / link, and the PWM inverter. Not shown is the energy storage device, presumed in this schematic to be a mechanical component (not an electrical one) supplying torque to the alternator. Additionally, the impedance of the block switching and distribution system was included. These devices are modeled with key physical characteristics for use in performance simulations.

The mechanical loads applied in the simulations include the inertial load of the craft, non-linear aerodynamic drag, and propulsion loads required to provide magnetic levitation based on an assumed passive electro-dynamic levitation (EDL) scheme.

The launch operation of both the induction and synchronous motor systems for the 455 kg craft was dynamically simulated. Both systems demonstrated the ability to successfully complete the 7g's acceleration launch to 300 m/s. Additionally, it was found that system-wide operating conditions were within reasonable physical ranges. A summary of the results of the dynamic simulations can be seen in Table 5.1.

Table 5.1 Dynamic launch simulation summary

Quantity	Induction	Synchron.
Electric energy input	37.2 MJ	34.35 MJ
Converted mech. energy	34.4 MJ	33.65 MJ
Delivered mech. energy	25.2 MJ	24.86 MJ
Converted energy efficiency	92.47%	97.96%
Delivered energy efficiency	67.74%	72.37%
Max. phase voltage	6.6 kV	6.6 kV
Max. phase current rms	11.3 kA rms	10.6 kA rms
Max. supply frequency	505 Hz	500 Hz
Max. electrical power	29.4 MW	29.25 MW
Max. force	73.2 kN	73.2 kN
Max. velocity	300 m/s	300 m/s

Another notable result of the simulations involved the electrical distribution system. The impedance of a distribution bus to the block switched stator segments was included in the simulations, and as a result, it was concluded that a single power source could be located near the launch end of the track, rather than multiple distributed power sources as initially assumed. This is due to the fact that the highest current draw occurs when the aerodynamic drag becomes substantial, at the high-speed end of the track. Transmission losses are therefore manageable at the beginning of the launch where the currents are lower, and the frequency is low. Figure 5.2 shows this possible distribution schematic.

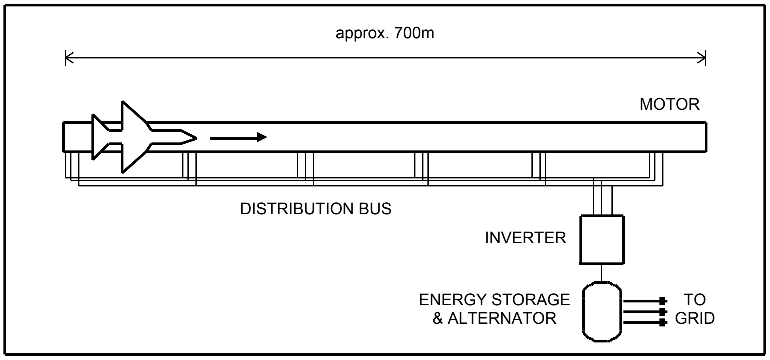

Figure 5.2 Single power supply distribution system

6 Performance Evaluation Comparison

From reviewing the simulation results, it is apparent that there is very little performance difference between the induction and synchronous designs in this case. Both systems met the launch performance requirements. Further, as their electrical operating characteristics are very similar, the power supply system required for each is also virtually identical. This result seems to indicate that in the linear launcher application, both types of motor can be satisfactorily designed for the task, and neither exhibits obvious performance advantages.

In general, the evaluation indicates that the comparison and trade-offs of the two motors in this application are similar to what would be expected from ordinary applications, under normal operating conditions. However, one notable difference exists in controls. Due to the high-speed operation of this machine, position error may become a dominant controls issue in properly orienting the stator field in the synchronous motor to maintain synchronicity. This effect even caused some difficulty during mere simulation of the machine. In contrast, a relatively large error in position and velocity can be robustly tolerated with the induction motor.

Estimated cost of the induction and synchronous motor based launch systems was very similar. The cost analysis figures for the two complete prototype launcher systems for the 455 kg craft were approximately \$27 million and \$29 million USD respectively, a difference of less than 10%.

7 Rotary Demonstrator

For testing the first prototype launcher of the 45 kg craft scale, a rotary embodiment of the linear motor is proposed. The test could demonstrate only the highest speed operation of the linear motor, which is presumed to be the most challenging aspect of this machine. This test unit can be designed to behave in a manner physically equivalent to a linear system, although being in a convenient rotary configuration.

The rotary prototype is a convenient test configuration for this system because it is far simpler to implement. It requires only a small portion of the linear motor to be constructed in order to demonstrate the machine. Additionally, a conventional motor could be used to bring the system to a high initial speed (at a low acceleration rate) so that only a short duty would be required of the prototype. For a demonstration of 7g's acceleration from 292 to 300 m/s, the motor and power system equipment could be built for only transient duty to substantially lower the cost and complexity.

8 Conclusions

A detailed design study of linear motors for aerospace launch assist led to baseline designs for induction and synchronous motors that were dynamically simulated in a launch, with realistic mechanical loads applied and realistic power supply characteristics. The performance of these machines was analyzed and both designs met the performance specifications, all with reasonable system operating parameters. As a next step, an experimental test of a prototype of each design is recommended to verify the simulation results.

It is significant that both motors exhibited normally expected behavior, even outside of their typical operating ranges. Neither design proved to have major performance advantages in this application beyond the conventionally held trade-offs between induction and synchronous motors. The selection of the preferable machine type will therefore be influenced by factors outside the scope of this study such as reliability, maintenance concerns, control system design, and integration with the MagLev scheme.

9 Acknowledgements

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