Technology Development for U.S. Urban Maglev

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Abstract

Key technical aspects of US Urban Maglev project are reported. The selected technology is based on the principle of electro-dynamic suspension (EDS) for levitation and linear synchronous motor (LSM) propulsion. High field permanent magnets (PM) arranged into Halbach arrays are used on the vehicle for the levitation, guidance and propulsion. The U.S. Urban Maglev project is a Federal Transit Administration (FTA) sponsored program directed toward development of maglev technology for urban mass transportation in the United States. Progress in technology development is reported up to the date of paper submission.

1 Introduction

A Maglev system is classified by the technologies adopted for its levitation and propulsion. The technology chosen by the U.S. Urban Maglev system is EDS/LSM similar to the MLX system but with vastly different magnet utilization. While the MLX uses superconducting magnets in null flux configuration, U.S. urban maglev utilizes permanent magnets(B_r = 1.4T) in a double Halbach array of null-current configuration[1,2]. The EDS is a desirable levitation mode because it is inherently stable without active control but has its share of technical difficulties. The EDS suspension is also known for its soft suspension and under-damped dynamics. This weakness is solved, in the present system, by employing a double Halbach array configuration. All EDS systems experience high magnetic drag at low speed. In the U.S. urban maglev, a very high efficiency LSM based on PM/Halbach arrays is used to achieve passive lift, guidance and propulsion. Use of the EDS/LSM system for the low speed Urban Maglev is a new approach and, when successful, will provide a new technical option for Maglev based transportation systems. The baseline design is based on performance prediction from code simulations and analyses, and limited test results. Verification of the key design parameters is underway and preliminary results are reported in this paper.

2 Technology Development Approach

Technology development began with an initial system study that led to selection of key parameters. Testing of small-scale models, starting with bench size experiments has progressed to testing full scale magnets arranged in Halbach arrays, running over a 3 m diameter wheel with a full-scale track around its perimeter. These tests have validated several aspects of the analytical model but fail to demonstrate the dynamics of a levitated mass having a secondary suspension and freedom in all 6 degrees-of-freedom (dof). The next stage of development will be to build and test a full-scale vehicle chassisand track sections to validate the fundamental operation and control of an actual vehicle. With the analytical models of levitation, propulsion and guidance validated, the final step will be to demonstrate all modes of operation on a suitable test track. This will demonstrate viability for commercialization.

2.1 System Selection

Selection of the technologies for the system are driven by the requirements. Some of the important requirements constraining the design are:

Basic Design Parameters/Requirements

Throughput	12,000 passengers/hour/direction
Speed, max	160 km/hr
Acceleration, max	1.6 m/s^2
Turn Radius, min.	18.3 m
Grade, max	10%
Levitation Gap	25 mm (nominal)

In the beginning of the project, a trade study was conducted to select the best levitation technology meeting the requirements of the UML. The technologies considered were:

1. EMS (Electromagnetic/Conventional)
2. EDS (DC Superconducting/Halbach)
3. EDS (AC Superconducting/Iron Core)
4. EDS (PM/Halbach)

Cost, technological difficulties and fundamental limits of each technology option were used in the trades. The trade study concluded that a system with PMs arranged above and below the conducting ladder track (Double Halbach) meets the requirements at minimum cost.

The large gap requirement for the UML eliminated the conventional EMS. The technical difficulties and weight of the cryogenic system for the DC superconducting option were prohibitive. The large amount of power required for the refrigeration and the weight of an iron core was a major disadvantage of an AC superconducting system. The PM/Halbach levitation system is a new technology that will require development before the system is fully verified. However, many advantages of the system make it a very promising technology option. The single-sided PM/Halbach system, however, induces a large magnetic drag force at low velocity and provides a very soft suspension. These problems were overcome with a double Halbach array as shown in Fig.1. In order to further minimize the power requirements, the vehicle was kept passive and a LSM was chosen as the propulsion motor.

2.2 Levitation System

A cross section of the vehicle chassis and track is shown in Figure 1. This shows the double Halbach arrays used for levitation at both side of the track and single sided Halbach array and LSM winding directly above. The propulsion and guidance are combined in the LSM, taking advantage of the partial iron-core machine. The LSM is designed to provide up to 60 kN of lift force and 25 kN of guidance force while providing 65 kN of thrust per vehicle.

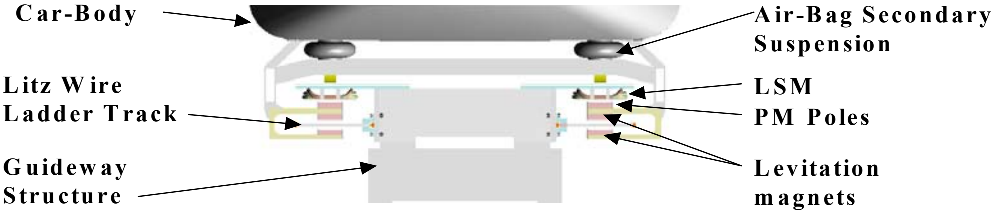

Figure 1. Cross section of Vehicle Chassis

The key technologies being adopted for U.S. Urban Maglev are made possible by a novel use of Halbach arrays, which enhances the useful magnetic field in the direction of motion while canceling much of the drag-producing field in the vertical direction. This is further made possible by recent advancements in permanent magnet technology, which produces magnets with a high remnant field

(1.4T), high energy density (300 - 400 kJ/m^3) and high coercivity (900 – 1000 kA/m). Figure 2 shows magnets in double Halbach array and ladder track.. The levitation gap is defined as the distance between the upper magnet and top of Litz wire.

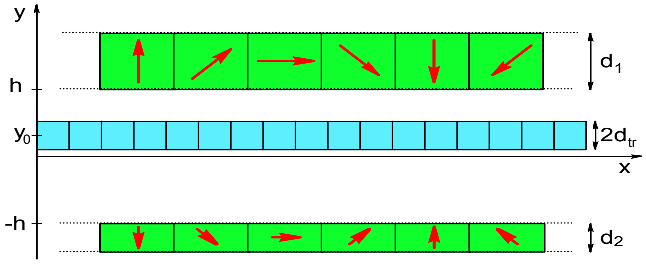

Figure 2. Permanent Magnets in a Double Halbach Array. The middle structure is the track.

The double Halbach array levitation system utilizes both sides of a ladder track having Litz wire rungs. This minimizes the drag and achieves a low lift-off velocity (<3 m/s). Two track configurations, ladder track with Litz wire rungs and laminated copper sheets are being considered at the present time.

A great deal of analysis has been carried out to predict the basic performances of the levitation, guidance and propulsion systems. Small-scale levitation tests have confirmed the basic analytical methods used for the full-scale systems. Figure 3 shows the levitation gap variation as a function of vehicle speed. The upper curve represents the gap of an empty vehicle (9500 kg) and the lower curve represents a fully loaded vehicle (16500 kg). The analyses predict a lift off speed of 2 to 3 m/s.

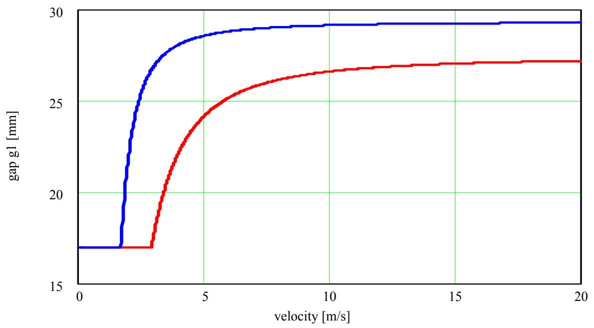

Figure 3. Levitation Gap Variation vs. Speed

The baseline levitation system for a vehicle is made of four magnet pads, each 9λ in length. One λ of the array is made of 8 magnets. The top array uses magnets of 50mm cube while the lower arrays uses thinner(40mm) magnets.

2.3 Test Wheel

Figure 4 shows a photograph of the test wheel built to verify the levitation performance including some limited dynamics testing. The wheel (with Litz wire rungs) rotates at a controlled speed through the gap between the upper and lower magnet arrays, which are mounted on a device that allows the magnet arrays to move only in the vertical Y direction. All other degrees of freedom are restrained. The magnet system mass and magnet footprint simulate 1/18 th of the fully loaded vehicle.

Figure 4. Test Wheel Assembly

Many interesting results have been obtained from the test. Initial testing began with a symmetrical arrangement of the upper and lower Halbach arrays. Each had 3 arrays arranged in rectangular canisters such that the arrays were effectively side-by-side (three of the same kind of magnet in each canister). This configuration, however, did not produce the expected lift because of the low average field and the inherent cancellation of the vertical field. This low average field was attributed to the end effects at the transverse edges of the magnet arrays and canceling of the vertical field. The test result was used to improve the simulation code. Subsequently, the test runs have been made on 5 arrays (single side) on top alone and in combination with 3 arrays on the bottom. The polarity of the present magnet arrangements, top and bottom, is symmetric except for the bias resulting from the upper array being thicker than the lower. Test results are shown in Figure 5 where lift and drag force measured are compared with pre-test predictions. The analyses also predicted a higher lift force when the lower magnet arrays are shifted in the direction of motion. Test runs have been made with both shifted and non-shifted configurations. Presently, the magnet holder has a capability to shift only 45°. The magnet holder will be changed later to allow any degree of shift. The test results from the shifted and non-shifted configurations are compared in Figure 6 . As was predicted, the shifted configuration generates more lift but the drag also is higher (Figure 6). The present analysis and simulation predict a shift around 30° will be optimum in terms of lift-to-drag ratio. Various combinations of magnet arrangement and shift angles will be tested to find the optimum configuration.

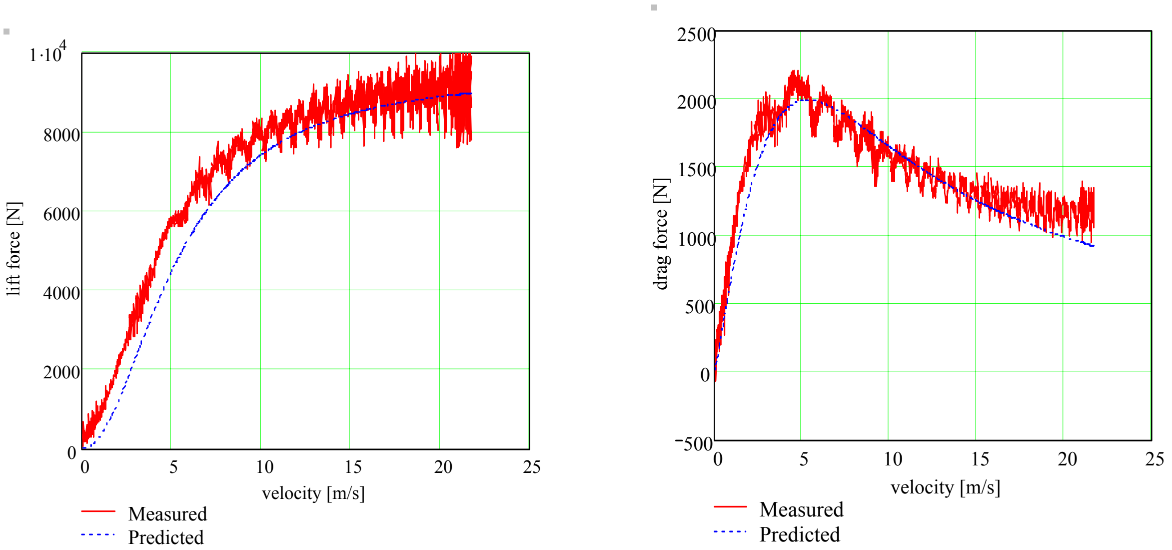

Figure 5. Fixed Gap Test results – 5 top/3 bottom without shift

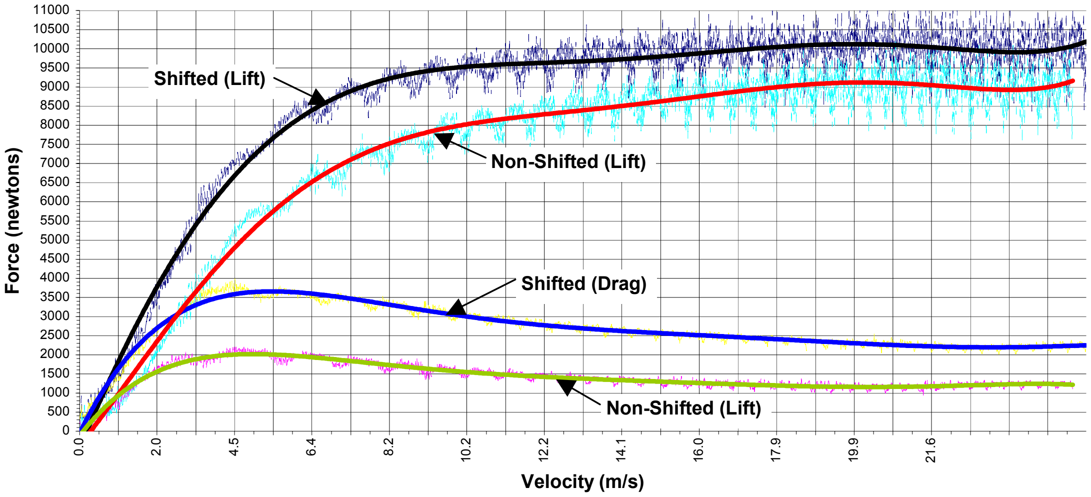

Figure 6. Comparison – Shifted vs. Non-Shifted

Figure 7 shows the preliminary results of the gap fluctuation dynamics. The gap fluctuation of the test wheel is created from the wheel runout(~3 mm) and compare with available EMS test data from a test track and full size vehicle. The present comparison seems to indicate that the ride quality of the U.S. urban maglev system will be comparable or better than EMS systems.

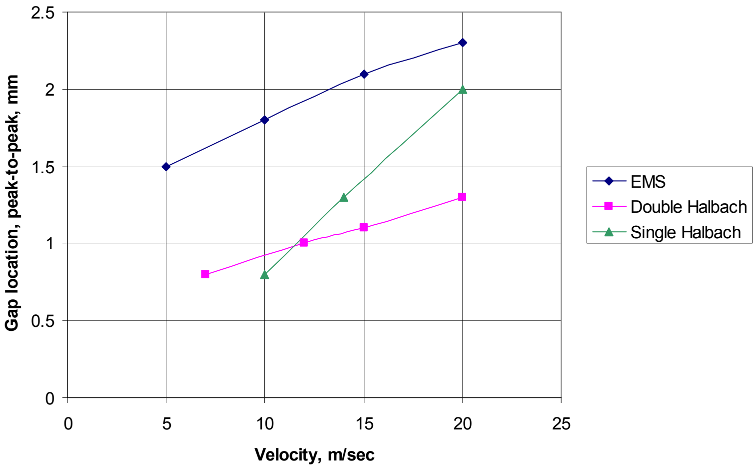

Figure 7. Gap Fluctuations Compared with Typical EMS Data

The test results also showed that the double Halbach system generates a small but measurable passive magnetic damping (Figure 8). The disturbance was generated producing a step displacement on the levitated magnet array; damping was measured as the logarithmic decrement of the decay in amplitude (~3%).

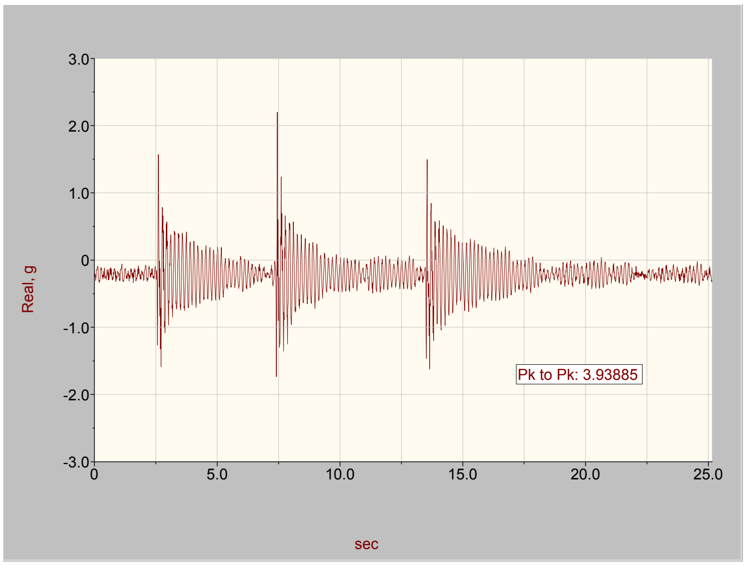

Figure 8. Magnetic Damping

2.4 Propulsion and Guidance

A cross section of the LSM is shown in Figure 9. The winding is partially iron cored and the excitation magnetic field is provided by the permanent magnets in single Halbach arrays. In this configuration, propulsion and guidance are combined. The LSM is designed to provide up to 60 kN of lift force, 25 kN of guidance force while generating up to 65 kN of thrust per vehicle. An inverter of 1.5 MVA is called for to power the LSM for each inverter block for a 4-car train. The LSM parameters are summarized in Table 1.

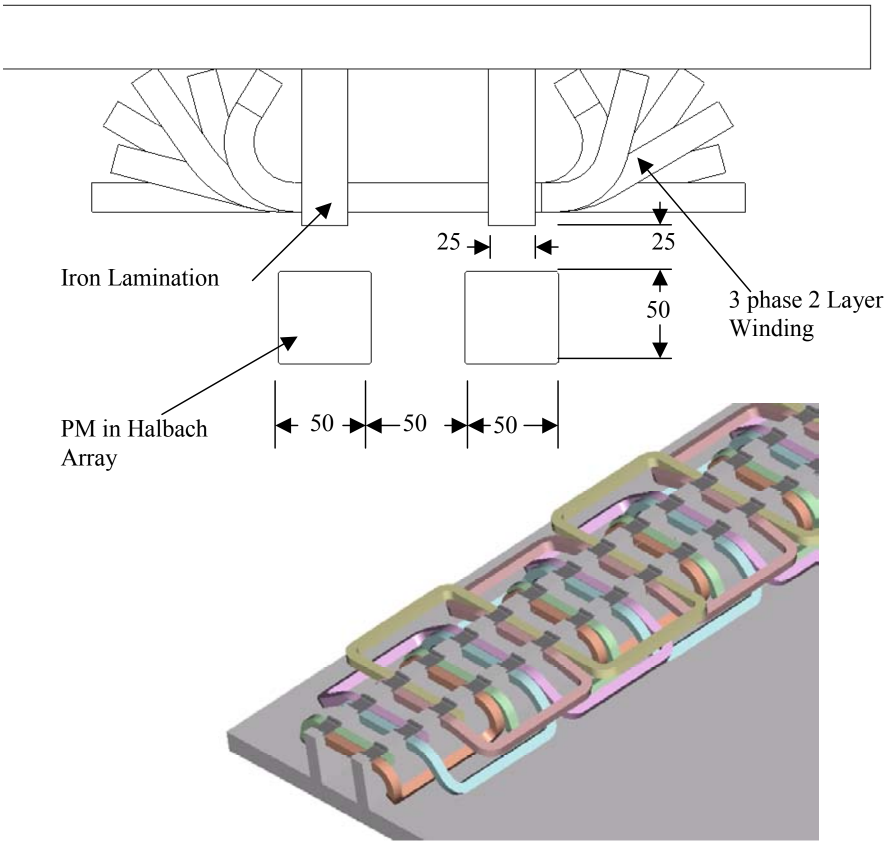

Figure 9. LSM Cross Section and Assembly

Table 1: LSM Parameters

Winding	3 phase, 2 layer
Thrust (peak)	67 kN
Current (peak)	3000 A
Passive Lift	65 kN @ 21 mm Gap
Guidance	25 kN @ 25 mm Lateral Displacement
Inverter	1.5 MVA/block-4 car train

Various verification tests are in the planning. A table top test is being planned to measure the guidance force and passive lift force and magnetic field at the cable location while varying the magnet locations in three directions. The thrust forces will be measured with small current in the winding. Verification of speed and location detection scheme and control algorithm will be conducted using the test wheel. These tests will verify most of the propulsion and guidance design parameters and allow reliable design of the full scale system.

3 Conclusions and Remaining Activities

The simulation and test results indicated that the levitation scheme is sound and well established. A few tests with small variations of magnet configuration will find an optimum magnet configuration for the levitation system. The present ladder track design with Litz wire rungs performed satisfactorily and remains as a viable track design option, but the laminated track with copper sheets seems a promising alternative because of its high reliability and manufacturing/cost advantage. The laminated track will be tested in the near future. A series of tests also will be conducted to verify the propulsion and guidance parameters and the control algorithm. A system level verification will be conducted on a test track using a vehicle chassis. A test track(~120 m) consisting of straight and curved sections with superelevation will be constructed to verify the vehicle level performance of key technologies. These test results will be reflected in the design of the demonstration track, which will verify all the system level characteristics and dynamics

4 Acknowledgment

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5 References

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