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A STUDY OF THE EFFECT OF USING ELECTRODYNAMIC WHEELS IN SERIES

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Abstract

The mechanical rotation of a radially positioned permanent magnet Halbach array above a conducting, non-magnetic, track generates a travelling time-varying field that can inductively create suspension and propulsion forces simultaneously. This ‘Electrodynamic Wheel’(EDW) could be used to create a relatively cheap form of maglev transportation since the track would only consist of thin sheets of aluminum and no track electrification is necessary. The effect of using multiple EDW’s in series is studied by using 2D steady-state finite element analysis. It is shown that the thrust efficiency can be considerably improved by increasing the number of EDW's used in series. A comparison is made between an EDW driven maglev vehicle and other maglev vehicle systems.

Keywords: maglev, electrodynamic, suspension, propulsion, Halbach array

1 Introduction

Maglev has many potential advantages over high-speed rail such as higher speed and acceleration capabilities, no rolling friction, lower track maintenance costs, quieter operation and superior ride quality [1]. Maglev high operational speed also enables it to compete with short-haul aircraft and uses significantly less energy [2]. Despite all of these advantages there is a strong reluctance to its use and many countries have decided to upgrade or install high-speed rail, or depend on short-haul aircraft and highways. It seems that maglev will only be able to truly compete with high-speed rail, aircraft and highway’s significantly lower capital costs if the maglev track is passive.

Passive track maglev designs were studied intensively in the 1970’s and early 80’s. The use of a single-sided linear induction motor (SLIM) with a track constructed of aluminum and back iron held early promise. But for high speed operation the SLIM suffers from a low power factor and it must be designed to be very long in order to counteract the end-effects [3,4]. In addition, a secondary suspension system must be used which increases costs and creates drag losses [5]. If the SLIM track is constructed only of aluminum then the induced track currents will also create a lift force, in addition to thrust. This ‘electromagnetic river’ concept, proposed by Eastham and Laithwaite [6] has a very poor power factor [7,8], and the lift-to-weight ratio is low, thus its practical implementation has never been realized.

Another passive track design proposed by Levi is the Homopolar Iron Cored Linear Synchronous Motor (HICLSM) [9-12]. This design has a salient iron track under a girder and the vehicle has a primary with a traveling AC and a DC excitation. The DC excitation provides an attractive lift force and magnetization field, while the AC windings are made to interact synchronously with the salient pole track structure so as to create the propulsive force. As large eddy current drag forces will be induced in the track at high speed [12] the track iron needs to be laminated. Also in order to prevent the iron from saturating the track iron must be made 1-2 times thicker than an equivalent SLIM iron track [13,14], this all adds up to a relatively costly passive track design.

A third possibility is to mechanically rotate radial or axial positioned magnets over an aluminum track [15-18]. The rotation of the magnets will enable a lift and thrust force to be created simultaneously. The creation of guidance force will be discussed in an accompanying paper. With this method the drag force that is created by electrodynamic suspension is used to create the thrust [17]. Also, as the magnets are inducing the track currents the power factor is not affected. Although increased losses result from the mechanical rotation, only one mechanism is needed to create all the forces, thus reducing the overall losses. This passive track system could be relatively cheap, with the track costs being comparable to rail. In this paper the effect of rotating a series of radially positioned permanent magnet Halbach arrays above an aluminum track is studied.

3 The Effect of Using Electrodynamic Wheels in Series

The Halbach magnets were modeled in 2D by using an equivalent complex current sheet on the outer rotor radius. The value of the current was determined by equating the value of the magnet magnetic vector potential to the magnetic vector potential created by the equivalent currents [18]. The use of the complex current sheet enabled both the rotational and translational motion to be modeled using a steady-state finite element model.

Previously it was shown that the thrust efficiency could be increased if a larger number of rotor pole-pairs were used, but this improvement is at the expensive of a lower lift-to-weight and lift-to-thrust ratio [18]. Another method of achieving higher thrust efficiency is to use a number of Halbach EDW's in series. If a second EDW is rotating closely behind the first, the second EDW will be able to use some of the currents induced in the track by the first EDW, and therefore the second EDW will not have to expend as much energy in order to create the same forces as the first. As an illustration, the current within a 10mm thick track is shown in Figure 1 for a 0.2m radius Halbach rotor, with a translational and circumferentially velocity of 80 ms^{-1} and 95ms^{-1} respectively. The rotor is centered at 0.5m. Clearly large currents are still present in the track after the EDW has past.

3.1 Two EDW's in Series

The effect of two EDW's in series has been compared with the performance achievable by using two EDW's that are not interacting, either because they have a large separation distance, or are on different tracks. An illustration of the field lines for two interacting EDW's is shown in Figure 2. While the results from the comparison are shown in Figure 3 to Figure 7. Both situations are at the slip which gives peak thrust efficiency. The parameters used are given in Table 1. The results show that with the additional rotor interacting, the slip needs to be larger before the thrust is made positive. However, a significantly higher maximum thrust is achievable, and this results in a higher thrust efficiency. In addition, a higher lift force can also be achieved, which results in a larger lift-to-weight ratio. The results show that there is a range of slip values where both the lift-to-weight ratio and thrust efficiency are higher than if the two EDW's were not interacting. A summary of the improvements in performance is shown in Table 2. The percentage changes that improve performance are been shaded.

3.2 Summary of Simulation Results for One to Five EDW's in Series

Encouraged by the potential improvements obtained by using 2 EDW's in series a study of the effect of using up to 5 EDW's in series was undertaken. The parameters used in the simulation are the same as given in Table 1, but the separation distance between rotors, *Sep*, and pole-pairs, *P*, were also varied. The phase difference between the rotors was kept constant because it did not improve the performance. A lift-to-weight ratio of 8 or greater was always ensured. A summary of the simulation results is given in Table 3. The peak thrust efficiency, η_p, and corresponding slip, *s*, is also shown. Rotor separation distances less than 0.125m were not considered because this created too large a field between the rotors. As the number of series EDW's increases the peak efficiency occurs at a lower pole-pair value. Like for the SLIM, the thrust efficiency improves with length [4,19], but even with 5 pole-pairs the series EDW's will be much shorter than a high-speed SLIM [4]

4 Comparison with Current and Proposed Maglev Technologies

A brief comparison between current and past high-speed maglev technologies and the EDW is now presented. Despite the difficulties in making comparisons, pertinent published results for a selection of LSM, SLIM and ICLSM designs, and 3 EDW designs, are presented in Table 4. The published track material requirements for each SLIM and ICLSM design is also shown. Although the EDW thrust efficiency is somewhat lower than the LSM and SLIM efficiencies, they do not include losses associated with providing the lift and counteracting the magnetic drag, while the EDW designs include these losses, The reduction in the EDW thrust efficiency shown in Table 3 to that shown in Table 4 is due to the inclusion of the estimated drive motor losses and windage and friction losses. The material requirements for the LSM have not been included, but the cost of the LSM will be far greater than for the other designs [20].

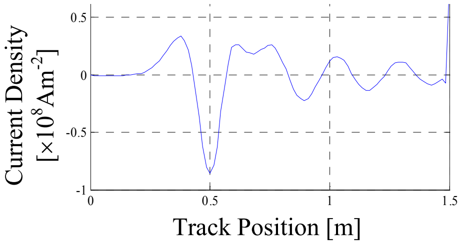

Figure 1. Current within the Surface of the Track

Table 1 Parameters used for the Two EDW Comparison

Translational Velocity	135ms^{-1}
Outer radius	0.23m
Pole pairs	6
Track Thickness	10 mm
Magnet Width	0.2 m
Air gap	10 mm
Rotor separation distance	0.175m
Track conductivity	3.5×107 Sm^{-1}

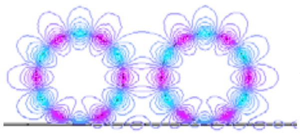

Figure 2 Two EDW's in Series Separated by 0.175m

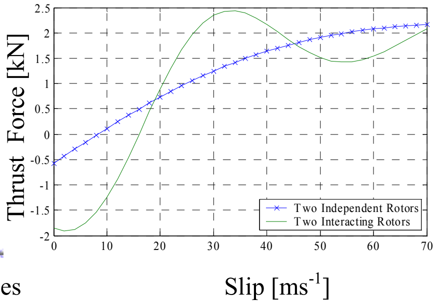

Figure 3 Thrust Force Comparison

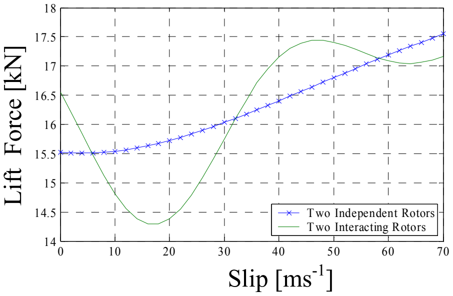

Figure 4. Lift Force Comparison

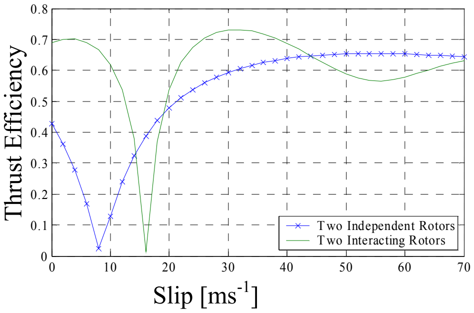

Figure 5. Thrust Efficiency Comparison

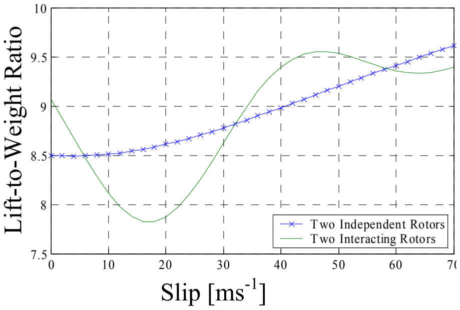

Figure 6. Lift-to-Weight Ratio

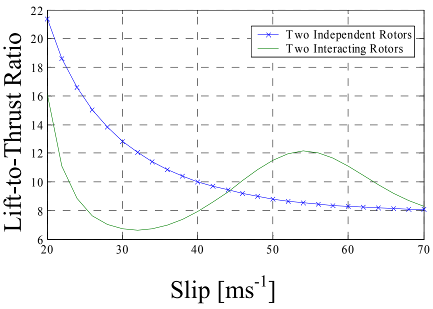

Figure 7. Lift-to-Weight Ratio

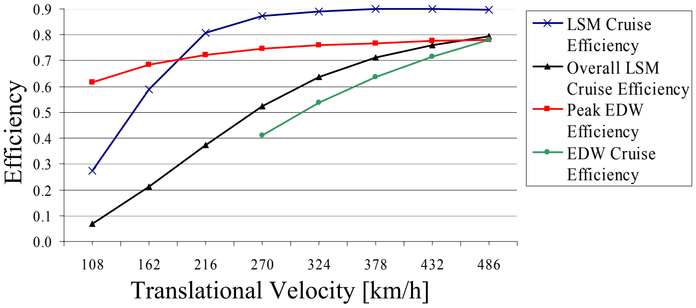

Figure 8. EDW Efficiency Comparison with LSM Maglev when Including Additional Losses

A comparison for the efficiency-speed profile for an electrodynamic suspension (EDS) system with a LSM is shown in Figure 8. The LSM and EDS data is from a study by Thornton [20]. Figure 9 shows both the LSM cruise efficiency and the overall efficiency when the other losses, such as EDS, eddy current and LSM losses, are included. To attain a 90% LSM efficiency the train length as a percentage of the active track must be very high [21]; For instance the MLX01 has 90% efficiency when the vehicle is over 40% of the active track. Such a high LSM efficiency would only be economically feasible in highly dense commuter corridors (as encountered in Japan). The EDW vehicle's peak efficiency is almost uniform throughout the operating range. This results in the EDW being more efficient than the LSM when accelerating at lower translational speeds.

4 Conclusion

The use of multiple EDW's in series can significantly increase the overall EDW's thrust efficiency while also enabling a satisfactory lift-to-weight and lift-to-thrust ratio to be obtained. It seems that it is possible for an EDW driven maglev, with only an aluminum sheet track, to be designed to be as efficient as an LSM driven maglev when the additional lift losses are included in the analysis.

Table 2. Improvement in Performance when Using Two EDW's in Series (at Peak Thrust Efficiency)

Parameter	*Two Independent Rotors*	*Two Interacting Rotors*	*% Change*
Slip [ms^{-1}]	54	32	-41
Lift force, F_L [kN]	17.0	16.1	-5
Lift-to-weight ratio	9.29	8.81	-5
Thrust force, F_T [kN]	1.99	2.43	+22
Lift-to-thrust ratio, F_L/F_T	8.54	6.64	-22
Track power loss, P_{Loss} [kW]	141.5	121.0	-14
Total power requirement [kW]	410	448	+9
Thrust efficiency	0.66	0.73	+11

Table 3. Peak Thrust Efficiency for Different Pole-Pairs and Rotor Numbers at 135ms^{-1}

EDW's in Series	**1**		**2**			**3**			**4**			**5**		
Pole-Pairs	η_p	**s**	η_p	**Sep.**	**s**	η_p	**Sep.**	**s**	η_p	**Sep.**	**s**	η_p	**Sep.**	**s**
3	0.57	92	0.70	0.325	50	0.76	0.35	40	0.79	0.35	36	0.81	0.375	30
4	0.61	80	0.72	0.175	38	0.78	0.175	32	0.81	0.175	28	0.83	0.200	22
5	0.64	66	0.72	0.250	42	0.77	0.125	10	0.80	0.125	8	0.80	0.300	26
6	0.66	54	0.73	0.175	32	0.77	0.175	28	0.79	0.175	26	0.81	0.200	20
7	0.67	54	0.72	0.250	32	0.77	0.125	16	0.78	0.250	28	0.78	0.250	28

Table 4 Thrust Efficiency and Material Performance Comparison

LSM Designs	*Efficiency, η*	*Power Factor, pf*	*$\eta \times PF$*	*Design Speed [km/h]*	*Active Track length [m]*	*Train Length to Active Track Length Ratio*
Japanese Maglev MLX01, 2004 [21]	0.91	0.91	0.82	500	1000	0.4
Transrapid, TR07 LSM [2]	0.87	0.73	0.63	480	300	0.15

Design	*Efficiency, η*	*Power Factor, pf*	*$\eta \times PF$*	*Design Speed [km/h]*	*Motor Length [m]*	*Est. Track Material Al/Fe [Tons/km]*
*SLIM Designs**						
Chuba HSST, 2003 [22,23]	0.64	0.64	0.41	200	2.3	3.6/26 (sheet)
Nonaka SLIM Design 1, 1987 [4]	0.87	0.69	0.60	333	7.98	2.1/20 (sheet)
Eastham SLIM Design, 1987 [3]	0.82	0.52	0.43	400	6	3.4/51.4 (sheet)
FRA LIMRV, 1978 [24]	0.67	0.58	0.39	400	7.6	-
*HICLSM Designs**						
Swissmetro, 2004 [11,25]	0.84	0.84	0.71	372	-	- (laminated)
Boldea HICLSM Design, 1979 [26]	0.84	0.99	0.83	360	-	- (laminated)
GE Homopolar LSM, 1978 [24,27]	0.88	1	0.88	400	-	0/86 (laminated)
GE Claw Pole LSM, 1978 [24,27]	0.84	1	0.84	400	-	0/262 (laminated)
*EDW Designs**						
Vehicle with Two EDW's in Series	0.67	1	0.67	300	1.3	16.2/0 (sheet)
Vehicle with Three EDW's in Series	0.72	1	0.72	400	1.9	16.2/0 (sheet)
Vehicle with Five EDW's in Series	0.75	1	0.75	500	3.3	16.2/0 (sheet)

* Efficiency and power factor at the terminals of the motor

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