Dynamic Modeling of an Electrodynamic Maglev Vehicle

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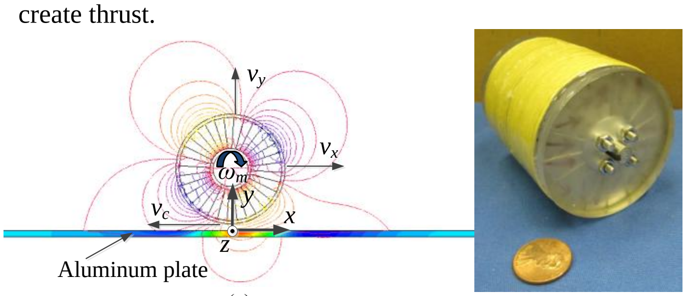
***Abstract*—. Paper digest outlines the numerical modeling of an electrodynamic maglev vehicle utilizing a steady-state eddy current modeling approach. The maglev vehicle's electrodynamic wheels are modeled utilizing an equivalent fictitious magnetic charge sheet. The predicted torque utilizing this approach is compared with the experimentally measured dynamic values.**

***Index Terms*—Eddy currents, Electromagnetic modeling, Magnetic levitation,**

I. Introduction

Electrodynamic maglev vehicles utilize eddy currents to create the suspension forces [1, 2]. By mechanically rotating magnetic rotors above a conductive aluminum plate eddy currents will be induced in the plate [3, 4]. The induced eddy current field will interact with the magnetic rotor to create tangential force, F_x, normal force F_y, and lateral force, F_z. This concept is illustrated in Fig. 1(a) and a constructed 2 pole-pair Halbach rotor is shown in Fig. 1(b). By rotating the magnetic source the detrimental drag force typically present in electrodynamic maglev systems [1, 2] can be used to create thrust.



(a) (b)

Fig. 1 (a) Finite element analysis model of a two pole-pair Halbach rotor rotating and translationally moving above an aluminum plate guideway, (b) Experimental 2 pole-pair Halbach rotor.

An experimental setup shown in Fig. 2 and Fig. 3 has been constructed in order to understand the dynamics when a vehicle utilizing four magnetic rotors, also called electrodynamic wheels (EDW), is operated. The vehicle has been kept translationally stationary and a 1.2 diameter guideway wheel which is being used to represent the flat aluminum track is rotated to simulate translational motion.

In [5] the 3-D forces were derived when utilizing the concept of a fictitious equivalent magnetic charge sheet function $\rho_m(x,0,z)$ located at the conductive sheet surface (y=0). The concept of equivalent magnetic charge is often utilized to model individual magnets [6, 7] but a magnetic charge sheet can also be utilized to replace an entire complex magnetic source such as a Halbach rotor [8]. It was shown in [5] that the magnetic energy due to the magnetic source and the reflected field is given by

$$U = \frac{1}{2}\mathrm{Re}\left\{ \int_{x=0}^{l_x}\int_{z=0}^{l_z} \rho_m^*(x,y,z)\phi^r(x,y,z)\,dxdz \right\} \text{ at } y=0 \quad (1)$$

where ϕ^r is the magnetic scalar potential created by the induced eddy currents. The integration is taken over the full surface of the fictitious magnetic charge sheet, $\rho_m(x,0,z)$. Utilizing (1) the force, torque, T, and power, P_s supplied by the rotating magnetic rotor are respectively [5]

$$\mathbf{F} = -\nabla U\Big|_{\rho_m=\text{constant}} \quad (2)$$

$$T = \frac{\partial U}{\partial \theta_m}\Big|_{\rho_m=\text{constant}} = -\frac{p\omega_M}{2}\mathrm{Re}\left\{ j\int_{x=0}^{l_x}\int_{z=0}^{l_z} \rho_m^*\phi^r\,dxdz \right\} \quad (3)$$

$$P_s = \frac{\partial U}{\partial t}\Big|_{\rho_m=\text{constant}} = jpw_m U \quad (4)$$

where ω_m=mechanical angular velocity of the rotor (rads^{-1}) and p=number of pole-pairs.

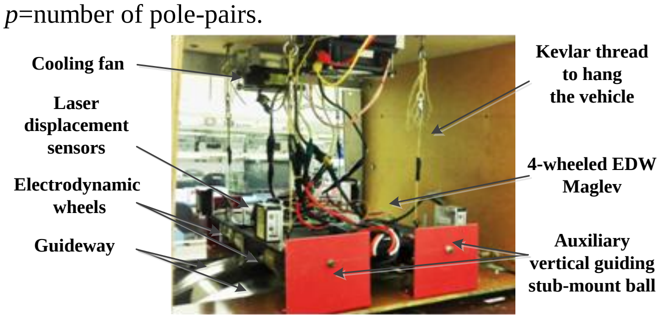


Fig. 2. Electrodynamic vehicle setup with four laser displacement sensor.

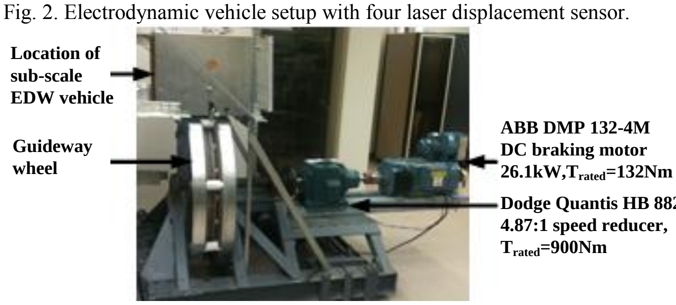


Fig. 3. Guideway setup with an in-line gear reducer and DC braking motor.

In order to understand the dynamic coupling between the forces, the experimental setup has been designed to prevent motion along the x and z directions as well as angular yaw. Four laser sensors are located at each corner of the vehicle and provide high fidelity air-gap displacement information. The vehicle is able to move in the *y* direction (heave) as well as rotate around the *x* and *z* axis (pitch, roll) as illustrated in Fig. 4. The heave, pitch and roll motion are defined as:

$$Heave = \frac{1}{4}[g_{fl} + g_{fr} + g_{bl} + g_{br}] \tag{5}$$

$$Pitch = \frac{1}{2L}[g_{fl} + g_{fr} - g_{bl} - g_{br}] \tag{6}$$

$$Roll = \frac{1}{2W}[g_{fr} + g_{br} - g_{fl} - g_{bl}] \tag{7}$$

where subscript *f*=front, *b*=back, *l*=left, *r*=right. *W*=width between vehicles sensors and *L*=length between sensors.

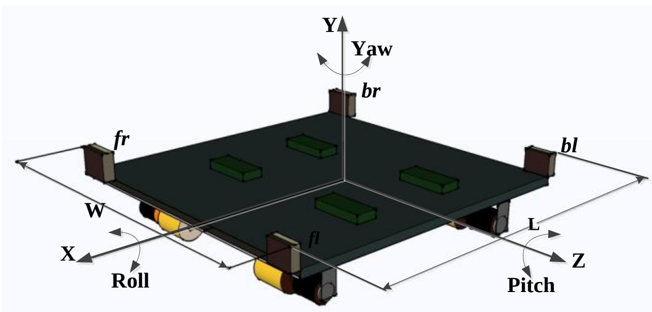


Fig. 4. Maglev vehicle coordinate definition.

By experimentally sensing the current drawn by the brushless dc (BLDC) motor controllers the torque required will be

$$T = k_t I_a \tag{8}$$

where k_t=0.0404N.m/A is the torque constant for the BLDC motor. The variation in the airgap, EDW wheel RPM and guideway speed are shown in Fig. 5. Utilizing the values measured from the experimental setup the torque calculated using (3) is shown in Fig. 6 along with the measured torque. Also Fig. 6 shows a comparison of output power for the measured and analytic model. The full paper will present a more complete comparison between experimental and numerically calculated forces using the 3-D eddy current model developed in [5]. Numerical approaches using 3-D eddy current stiffness and damping equations derived in [5] will also be utilized to minimize the heave, pitch and roll motion.

Conclusion

This paper outlines the application and validation of an analytically derived (but numerically computed) 3-D eddy-current force and torque calculation approach for an electrodynamic wheel maglev vehicle.

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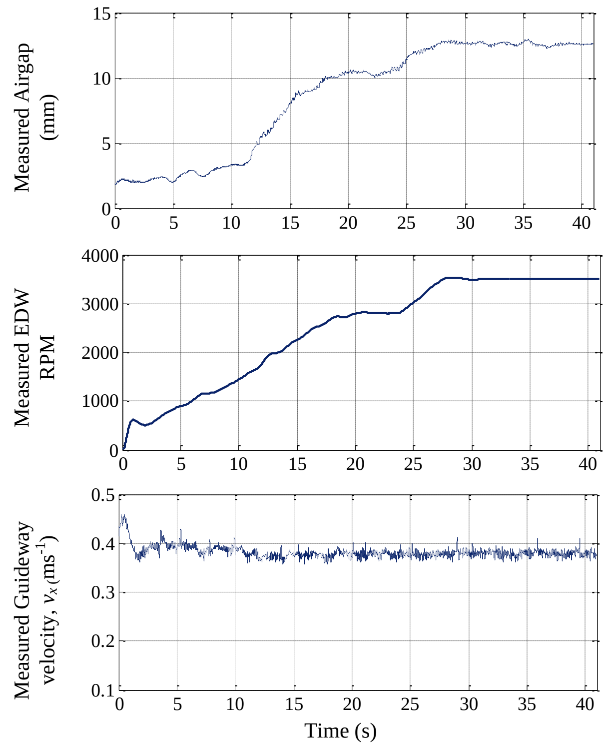

Fig. 5. Measured airgap, EDW rotor RPM and guideway velocity

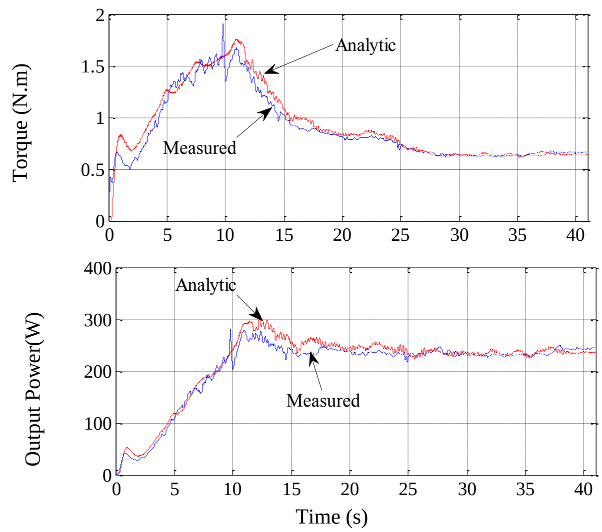

Fig. 6. Comparisons of the rotor torque and output power between analytic and experimentally measured values are shown.