A Mechanical Innovation to Improve the Railroad

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Abstract

The scope of research focuses on exploring a mechanical innovation to modernize the railroad without the extensive and costly altercation of infrastructure. Redesigning the propulsion system of a commuter railcar to match the performance of a Maglev train could potentially increase acceleration rates, enhance traction capabilities, and advance systematic operation. A design featuring a linear motor arranged radially along the wheel of a train could accomplish this ambitious initiative and has proven successful in the elevator industry with the birth of the KONE EcoDisc.

1. Introduction

Railcars operating throughout the Northeast are still built with bogies designed with concepts from the 20th century. A simple idea inspired by an elevator ride could one day lead to the mechanical innovation that transforms the manufacturing of railcars into the 21st century. The goal of the research was to determine the preliminary feasibility of redesigning the traction motors in electric commuter trains. By arranging a linear motor into a radial alignment, the motor can be integrated into the wheel of the train. To better understand the performance of the traction motors, field data was collected during the project to calculate the railcars acceleration in revenue service. All data was obtained from the perspective of a passenger bearing a monthly commuter ticket. Since the electrical systems researched are complex to understand, for this project's purpose, the research consists of basic explanations and simplified models using the fundamental laws of physics.

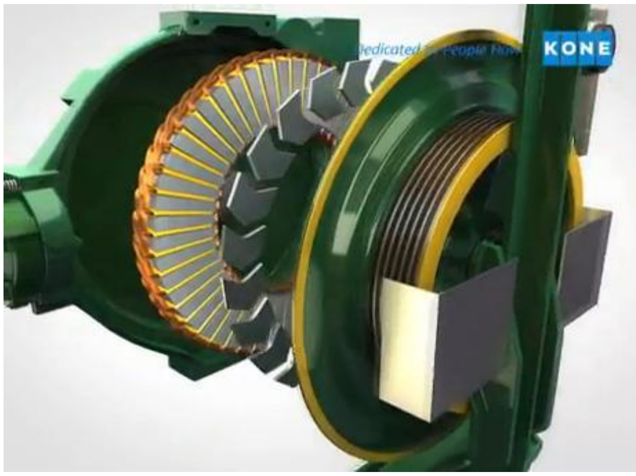

Figure 1: KONE EcoDisc Design.

2. Rotational Application of Linear Motors

The KONE EcoDisc is an axial synchronous hoisting motor designed for a lineup of elevator applications [1]. In 1996, KONE engineers explored the feasibility of using linear motor technology in the elevator industry, similar to this project's motive with railcars. They paralleled this innovation with the conception of the Maglev train. Engineers extruded the design of the traditional motor into a linear fashion and reintroduced a 360° rotation. Shaped like a disk, the resulting design is flat and axial, where magnets are compact and specifically shaped to integrate into the elevators hoisting sheave.

The EcoDisc is thin enough to place between the elevator guiderail and shaft wall. The EcoDisc is essentially a rotating magnetic field driven by a traction controller that provides a direct turning force on the motor. The EcoDisc is a synchronous motor, therefore there is no slip like in an induction motor commonly used on railcars. Performance wise, a smooth and quiet ride is produced and no gears are required. Applying this ideology to the wheel of a train will introduce the benefits of linear motors.

3. Existing Propulsion in Electric Trains

The purpose of the propulsion system in the train is to convert electrical energy into mechanical energy that provides the operational motion of the train. The New Haven Line was selected for the scope of research due to its proximity to the University of New Haven. For its commuter operations on the New Haven Line, MetroNorth recently transformed its backbone fleet from M-2 to M-8 railcars. Both the M-2 and the M-8 are electrical multiple unit railcars that share operational equipment between a pair. The M-2 had its first revenue run in April 1973, was produced by General Electric Transportation Systems, sports four 162 HP DC Motors (648 HP total per car), and uses a camshaft-resistance relay-logic system for traction control [2]. The M-8 had its first revenue run in March 2011, was produced by Kawasaki Heavy Industries, sports four 265 HP AC Motors (1060 HP total per car), and uses a Variable Voltage Variable Frequency (VVVF) drive with Insulated Gate Bipolar Transistor (IGBT) inverters for traction control [3]. The performance of the railcars must promise the timely operation of the New Haven Line and use effective acceleration between station stops.

Figure 2: An M-2 (left) and M-8 (right) sit in the New Haven Yard.

The electric propulsion of the M-8 railcars closely reflects the electrical operation of the KONE EcoDisc, but does not take advantage of a linear motor concept. The traction motors on the M-8 railcars operate on alternating current and are built as asynchronous induction motors. Induction motors have a stationary component called the field coil and a rotating bar called a rotor. The motor uses the magnetic induction of the coil and the magnetization of the rotor to produce a torque, which creates rotation through the interaction of alternating current flowing through the two assemblies. An AC voltage is applied to the field coil causing an alternating current to flow through the coil and creates a spinning magnetic field. This causes the rotor to attempt alignment with the spinning magnetic field. Torque is generated because the rotor speed is always slightly less than the speed of the magnetic field, known as slip. With connection to a suitable shaft, torque will provide work on a rotating mechanical load. Now becoming popular and suitable for heavy-duty application, the rotor itself is being installed as a powerful permanent magnet. This is the case with the KONE EcoDisc.

Alternating current is defined by both its frequency and voltage. The M-8 collects the electrical power using its pantograph or third rail shoes, depending on the territory that the M-8 is operating within. It then feeds the current through a transformer to step down the voltage. The current is then transmitted through a DC link to the IGBT inverters for precise traction control. The inverters receive direct current and output three separate alternating currents for the three-phase AC motor operation. This technique is called Pulse Width Modulation (PWM), which synthesizes a quasi-sinusoidal alternating current for traction motor usage. Computers aboard the train use both live and set parameters to command the IGBT inverters an appropriate firing rate to provide the proper output ratio of frequency and voltage. The frequency of this current will determine the upper limit of the rotational speed of the motor. Frequency dictates the timing of the polarity change between the poles of the motor. This rate directly controls the rotational speed of the motor. The applied voltage will determine the upper limit of the motor's torque. Torque is the rotational force that the train needs to produce in order to accelerate. The force that the motors in the M-8 produce is dependent on the motor's input voltage. A high voltage input derives a high current input as described by Ohm's law, assuming that the motor has a constant resistance value. Thus, a high current input results with a high power output. Variable frequency controls the differential forces in the AC motor. This can be described as the rate of attraction and repulsion between the field coil and the rotor. Variable voltage controls how much current is applied to the motor, which derives the intensity of the applied current. The current intensity determines the magnitude of the magnetic field produced between the core and magnets, which is responsible for how much force is applied to the rotation of the motor. Varying both the frequency and voltage of the alternating current into the traction motors is responsible for the acceleration of the M-8.

Unlike the quieter M-2 railcars, the M-8 motors generate audible harmonic distortion due to magnetostriction that can be heard when the train is accelerating or decelerating [4]. Magnetostriction is the phenomena where certain magnetic materials change dimensions when a magnetic flux is induced into them. Since the motor is made of magnetic materials, it is susceptible to magnetostriction and generates acoustical noise. The compressive forces caused by magnetic flux inflict a volume change that causes synchronized fluctuations in air pressure and density. The time rate of change of air pressure is equal to the time rate of change of the magnetic flux that caused it. Therefore, the intensity of the noise is directly related to the intensity of the magnetic fields inside of the motor. The motor will be louder when heavily loaded and at initial startup. As the train accelerates from start to its highest at running speed, the order and frequency of pulses changes to modulate voltage and provide desired motor power. The changing frequencies generate sound waves within the human ear range of 15 Hz–15 kHz, which allows passengers to detect the harmonics of the motor operation. The noise produced by the motor when the controller performs a step change is comparable to the transformation in pitch when a car changes gears. A complete understanding of how this is accomplished requires familiarity with Electrical Engineering and complex mathematical concepts of infinite series. One of these series is the Fourier series, which translates mathematical expressions in the time domain to the frequency domain.

4. Results: Observations and Data

Research was conducted on the M-8 propulsion from a restricted passenger perspective to observe its acceleration performance in revenue operation. Acceleration is the first derivative of velocity with respect to time. It can be approximated by the average acceleration when frequently measured. The average acceleration can be calculated if the change in speed is known during an observed time interval. For every mile per hour the M-8 increases, a lap is recorded and archived on a stopwatch. During the trial, the engineer applied a maximum acceleration rate to the controller. The engineer departed Harrison, NY en route to Mamaroneck, NY approximately 1.7 miles away. The M-8 reached 70 MPH, therefore, 70 laps were recorded and organized into an Excel spreadsheet. By dividing the change in speed over the change in time for each lap, the average acceleration was calculated for each mile per hour the M-8 accelerated. Figure 3 displays calculated values of this acceleration:

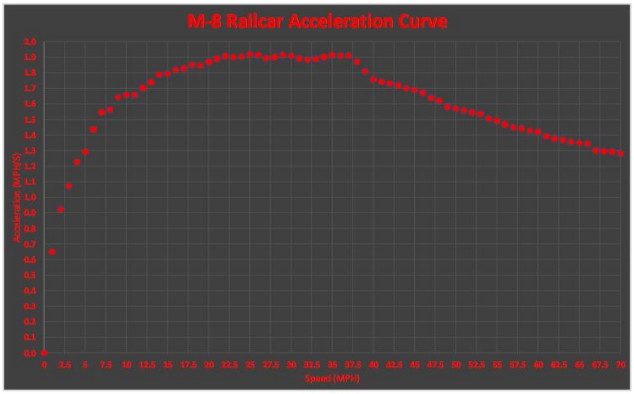

Figure 3: The acceleration of an M-8 railcar (in MPH/s) as a function of its speed (in MPH).

The M-8 is rated for an initial 2.0 MPH/s maximum acceleration. The field data accurately represents the technical specification of the M-8 railcar and follows the laws of physics. The curve creates a picture that describes the physical nature of the M-8 acceleration and reveals the speed at which the M-8 begins to loose its tractive effort, or ability to accelerate. While disregarding the effects of air resistance and additional forces acting upon the M-8, its acceleration effort can be described using two equations:

$$P = Fv, \tag{1}$$

$$F = Ma = M\frac{dv}{dt}, \tag{2}$$

where P is power, F is the magnitude of force, v is the magnitude of velocity (speed), M is mass, and a is the magnitude of acceleration. Equation (2) is Newton's second law of mechanics for linear motion.

During initial acceleration, the engineer calls for a maximum acceleration rate. Power is described as a function of force and velocity in Equation (1). The initial acceleration rate for the M-8 is constant at 2.0 MPH/s. The mass of the M-8 is also constant during acceleration, because there is no boarding while the train is in motion and the car body itself will loose no mass. If mass and acceleration are both constant, force is also constant by Equation (2). As the train is accelerating, its velocity is increasing. According to Equation (1), if the applied force is constant, the applied power is increased as the speed of the train increases. The M-8s are rated for 1060 HP per car, so as the train continues to accelerate and its speed increases, it approaches its maximum power value. When the M-8 reaches a full application of 1060 HP, a tradeoff must occur to preserve the integrity of physics. If power becomes constant and speed continues to increase, Equation (1) calls for the force to decrease. If the force begins to decrease and the mass of the M-8 remains constant, Equation (2) states that acceleration will decrease as well. While the M-8 continues to accelerate after it applies maximum power, its acceleration rate is reduced gradually with each increase of speed. Eventually, the opposing forces such as air resistance and friction balance the driving forces of the M-8 and maximum speed is reached.

Equations (1) and (2) describe the linear case of power and force respectively. Two equations parallel the linear motion of the train with the rotational motion of the motor:

$$P = \tau\omega, \tag{3}$$

$$\tau = I\alpha = I\frac{d\omega}{dt}, \tag{4}$$

where τ is the magnitude of torque, ω is the magnitude of angular velocity (rotational speed), I is moment of inertia, and α is the magnitude of angular acceleration. Equation (4) is Newton's second law of mechanics for rotational motion.

According to Equation (3), power is a function of torque and rotational speed. During the initial acceleration of the M-8, torque of the motor is constant while power input and the rotational speed of the motor are increasing. When the M-8 reaches its maximum power output, torque decreases in order for rotational speed to increase. Torque is a function of moment of inertia and angular acceleration as described by Equation (4). Therefore as the value of torque falls, the moment of inertia remains constant and the value of angular acceleration falls.

5. Discussion

The ten-week duration of this research project concluded with a multidisciplinary comprehension of the propulsion systems in electric railcars. The collected field data accurately reflected the specified acceleration rate of 2.0 MPH/s for the M-8 railcar. The data also reflected the fundamental laws of physics and demonstrated how acceleration is affected with increasing speed. A possible extension of this work would be to add rotational friction between the train wheels and the rail track (represented by a coefficient α) and the resistance force exerted on a moving train by the air (represented by a coefficient β). Including these two forces in Equations (1) and (2) gives [5, 6]

$$M\frac{dv}{dt} = \frac{P}{v} - \alpha v - \beta v^2. \tag{5}$$

This nonlinear differential equation could be solved and its solutions could be compared with the experimental data.

Comparing the M-2 and M-8 railcars described the evolution of propulsion equipment over the span of four decades. Additionally, the operation of the M-8 propulsion appears to relate to the operation of the KONE EcoDisc, suggesting a design featuring an axial synchronous motor may be feasible in future procurements. An axial motor integrated into the train's wheel, similar to the axial motor integrated into the elevator's sheave, would provide torque directly to the wheel of the train. Currently, the M-8 motor is indirectly connected to the wheel by a gearbox and axle. This new design could potentially remove the need for gearbox, increase the traction of the train, and prevent chaotic wheel slip conditions. It may also provide a higher power output and thus a longer sustained maximum acceleration rate. Without a deeper background in Electrical Engineering and access to additional technical specifications of the M-8 railcar, it is difficult to determine how efficient, reliable, and cost effective the design is.

6. Looking Forward

The project highlighted the importance and effectiveness of cross-discipline ability. While Civil Engineers do not design the propulsion in railcars, they are active in the procurement process. A well-rounded understanding of Mechanical and Electrical Engineering, in addition to Physics and Mathematics, will provide a Civil Engineer with the background necessary to collaborate with colleague engineers on future projects.

There will always be a demand for electric train procurement in the Northeast. It is important to invest in developing technology to increase the efficiency of electric motors. If such a design were proven feasible, it would transform the design of the traction motors on future railcars. To move forward with the research will require additional field data describing the electrical and power performance. With proper data and expertise, a collaborative team of engineers, physicists, and mathematicians can predict the success of a future design implementing linear motor technology.

Figure 4: Researcher Daniel Delgado with M-2 (left) and M-8 (right).

References

[1] https://www.youtube.com/watch?v=_j4fMLUQsO0.

[2] https://en.wikipedia.org/wiki/M2_(railcar).

[3] https://en.wikipedia.org/wiki/M8_(railcar).

[4] Ralph Prete, Electrical Engineer, SEPSA (private communication).

[5] L. D. Landau and E. M. Lifshitz, *Mechanics* (Pergamon, 1976).

[6] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Pergamon, 1987).

Acknowledgments

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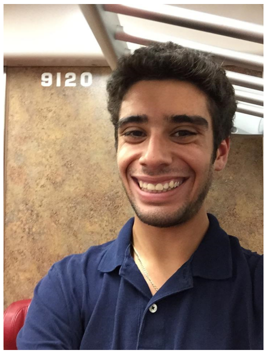

Daniel Delgado is a junior in the Civil Engineering program in the Tagliatela College of Engineering at the University of New Haven with a minor in Sustainable Studies.

He was encouraged to participate in undergraduate research by Dr. Nikodem Poplawski, the UNH Physics Coordinator and a renowned physics expert with extensive theories about black holes and the origin of the universe. Daniel approached Nikodem after a physics lecture and shared a spreadsheet he organized that contained an array of train specifications and data.

Daniel has been passionate about trains since childhood and hopes to work for MetroNorth's New Haven Division as a Professional Civil Engineer.