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Design of an Eddy Current Brake System for the Use of Roller Coasters Based on a Human Factors Engineering Approach

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Abstract**—**The goal of this paper is to converge upon a design of a brake system that could be used for a roller coaster found at an amusement park. It was necessary to find what could be deemed as a "comfortable" deceleration so that passengers do not feel as if they are suddenly jerked and pressed against the restraining harnesses. A human factors engineering approach was taken in order to determine this deceleration. Using a previous study that tested the deceleration of transit vehicles, it was found that a -0.45 G deceleration would be used as a design requirement to build this system around. An adjustable linear eddy current brake using permanent magnets would be the ideal system to use in order to meet this design requirement. Anthropometric data were then used to determine a realistic weight and length of the roller coaster that the brake was being designed for. The weight and length data were then factored into magnetic brake force equations. These equations were used to determine how the brake system and the brake run layout would be designed. A final design for the brake was determined and it was found that a total of 12 brakes would be needed with a maximum braking distance of 53.6 m in order to stop a roller coaster travelling at its top speed and loaded to maximum capacity. This design is derived from theoretical calculations, but is within the realm of feasibility.

Keywords**—**Eddy current brake, engineering design, human factors engineering.

I. INTRODUCTION

ROLLER coasters are among the most popular and common types of attractions at theme parks today. Because of this popularity, a theme park would want to make a roller coaster accessible to as wide a range of guests as possible, while still not compromising the thrills that are expected. Most roller coasters tend to operate at high speeds up until their brake run, which results in a sudden and sometimes harsh deceleration. Most braking systems implement friction to stop the train. However, the most recent development in roller coaster braking systems is magnetic brakes. These brakes work when conducting fins located on the roller coaster's cars pass through a row of neodymium magnets. The fin and magnets never come in contact with each other, but the incoming velocity of the conducting fin between the magnets induces an eddy current in the fin, which then creates a retarding magnetic braking force. The use of magnetic brakes allows for a gradual and more controlled deceleration. It is the purpose of this paper to design a roller coaster magnetic braking system that could be deemed comfortable to the passengers on board.

II. PROBLEM DEFINITION

The main problem in designing a brake system with comfortable deceleration is being able to determine what exactly is comfortable. From a design perspective, a human factors engineering approach should be taken to solve this problem. For the purpose of this project, human factors can be defined as discovering and applying information about human behavior, abilities, limitations, and other characteristics to the design of machines, systems, and environments for safe, comfortable, and effective human use [1]. For this project it will be important to determine what the limitations of the human body are when it comes to deceleration.

A study by the U.S. Department of Transportation was performed in 1977 to determine what would be an acceptable deceleration for public transportation vehicles. The study attempted to determine through tests and subsequent surveys how human test subjects felt after experiencing various braking scenarios. The study used subjects in the weight range of the 5th percentile adult female to the 95th percentile adult male. It was able to determine at what deceleration passengers of public transit, who are not restrained, would be able to remain securely in their seat. The study found that 84% of occupants remained seated in an emergency stop scenario at 0.47 G [2]. To corroborate this, a test was performed by the author of this paper in order to determine actual values of a roller coaster train going into its final brake run. During this point, the velocity went down from 14.15 m/s to 0.59 m/s in 10 seconds and the accelerometer recorded highs of 0.50-0.70 G [9]. Using the aforementioned study as a template it will be decided that a maximum of 0.45 G will be used. This deceleration should not give the passengers the sensation of sliding out of their seats; therefore they will not feel as if they are being pressed against the restraints.

III. DESIGN PROCESS

It is ideal to be able to adjust the brake force of the magnets in order to create the desired deceleration. One system that stood out from research had the ability to incrementally adjust the brake force by shifting the magnets' polarity [3]. This idea of incremental adjustment was used as a template going forward. Unfortunately, there are limited resources to

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determine the effect that shifting polarity between magnets has on magnetic brake force. However, there is abundant research and equations that support that the change in the air gap between the magnets and the induction fin will change the magnetic brake force [6], [8].

Synthesizing the incremental brake that shifts polarity with the change in air gap research allows for a brake system to be proposed. This brake will keep the magnets facing their polar opposites and will incrementally increase the distance between them and the incoming induction fin located under the roller coaster cars. Theoretically, each incremental increase in air gap distance will decrease brake force until the point the force becomes negligible, thus making the brake inactive. The movement of the magnets will work in a similar way to the template system in which two pushrods in conjunction with a servomotor will displace both rows of magnets connected to plates in a direction away from and perpendicular to the induction fin.

IV. Eddy Current Brake Background

Magnetic braking is caused by induced eddy currents which are dictated by Lenz's law. This law states that the direction of the current induced in a conductor (induction fin located on roller coaster) by a changing magnetic field is such that the magnetic field created by the induced current opposes the initial changing magnetic field [4]. Fig. 1 shows a metal plate moving with a velocity, v, through a magnetic field, *B*. As the left side of the plate draws nearer to the magnet, the magnetic field through the plate is increasing. Due to Faraday's law, this field induces a counterclockwise flow of current, *I*, in the plate. This is the eddy current and it produces an opposing magnetic field and due to Lenz's law opposes the change in the magnetic field, which in turn creates a drag force on the plate that is equivalent to a magnetic brake force. Conversely, on the right side of the plate as it moves away from the magnet, a clockwise eddy current is induced and a magnetic field is produced in the opposite direction.

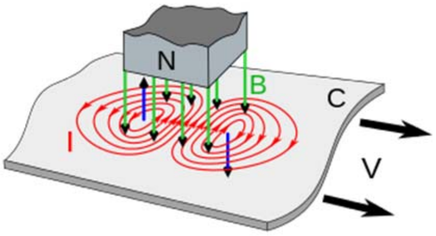

Fig. 1 Visual representation of a linear eddy current brake

Most experiments conducted to solve for magnetic brake force were performed on disk eddy current brakes (ECBs) that measured torque. For roller coasters, linear ECBs are used, but the principle is the same. To solve for a linear brake force, it has been proposed through research [5] that it can be approximated by:

$$F_b \approx \frac{1}{2} B^2 \sigma A t v \tag{1}$$

where B = magnetic field, σ = electrical conductivity of the induction fin, A = area of fin, t = thickness of fin, v = velocity of fin in the air gap. Equation (1), although just an approximation, is the best model to use for designing the linear ECB for this project. The variables in (1) will help determine the size of the conducting fin (A, t) and the material used (σ). Knowing the desired deceleration of 0.45 G, then the needed brake force can be found once the mass of the roller coaster train is determined. Velocity can be given a range of possible values, so that leaves determining the magnetic field. It can also be seen in (1) that if B is increased or decreased, then F_b will be changed accordingly. A test previously performed [5] gave a graphic representation of how brake force is related to velocity at three different air gaps of 3.9 mm, 4.8 mm, and 6.4 mm. Using this information, it was then possible to work backwards and plot the correlation between air gap and magnetic field (see Fig. 2).

An average estimate (shown with a circular marker in Fig. 2) of all the data points is used as a representation of how the magnetic field changes with the air gap for this particular experiment. Equation (2) was used to determine the effect that the geometry and grade of the magnets had on their magnetic field:

$$B = \frac{B_r}{\pi}\left[\arctan\left(\frac{LW}{2z\sqrt{4z^2+L^2+W^2}}\right) - \arctan\left(\frac{LW}{2(D+z)\sqrt{4(D+z)^2+L^2+W^2}}\right)\right] \tag{2}$$

where B_r = remanence field (magnet property determined by grade), L = length of magnet, W = width of magnet, z = distance from magnet pole-face, D = thickness of magnet. 35 neodymium magnets (N35) should be used to decelerate a theoretical roller coaster with given parameters. Other studies use this same magnet grade, so it can be assumed initially that this grade can be used for the purpose of this project [6]. A similar magnet size to that of a previous study [5] will be used to test the magnetic field and how it changes with respect to increased distance from the magnet pole-face. Equations (1) and (2) will dictate the final brake design. In order to get as realistic a design as possible, certain parameters need to be determined based on real world data and specifications.

V. Design Parameters

Newton's second law of motion, $F=ma$, will be used as the equivalent brake force necessary to decelerate the roller coaster with a = -4.41 m/s^2 (0.45 G; a is negative due to deceleration). Therefore, F from Newton's second law will equal F_b from (1) while not taking into account outside factors such as friction and aerodynamic drag. It is assumed that the roller coaster will hold 24 riders per train. The minimum height requirement of the passengers will be 48 inches, which will help determine the weight range of the passengers, thusly affecting the brake force necessary. The cars used for this project have an estimated weight of 908 kg (2,000 lbs.) and will fit four passengers each. This estimate includes the weight of the harnesses, wheels, and linkages. Therefore, the total weight of an empty car is 5,448 kg. Weight data for the passengers were determined through an anthropometric study done by the U.S. Department of Health and Human Services that logged the weight of a sample of children and adults in the United States from 2007-2010 [7]. It will be decided to take 20.4 kg (45 lbs.) as the lowest weight of any passenger that meets the height requirement. This data will be used to confirm that the brake designed will not exceed the desired deceleration when the train is filled with the lowest weight possible. Conversely, it is necessary to find the maximum weight of the roller coaster's occupants. Using the same anthropometric report, it was found that the 95th percentile adult male weighs an average of 127 kg [7]. Taking the weight data found, it can be determined that the roller coaster being designed will weigh between 5,938 kg and 8,496 kg when filled with passengers of the given extremes. This correlates to the brake having to be able to produce approximately 37,500 N of force in order to decelerate the roller coaster train at no greater than 0.45 G when it is fully loaded at maximum weight capacity.

VI. FINAL DESIGN

For all dimensions of the fin, it would be ideal to use as little material as possible so not to add too much weight to the roller coaster and to keep costs down. Al6061 will be used as the induction fin material for this project based off a previous study [8]. It will be assumed that 50 mm x 50 mm x 12 mm N35 magnets will be used and that the velocity of the roller coaster will be between 11 m/s and 18 m/s. For the larger scale of this project it was decided to have the magnets be able to move in a range of 3 mm to 10 mm away from the induction fin. This would change the magnetic field of one magnet from 0.21 T to 0.159 T respectively. Through several iterations, it was found that a fin 0.75 m long and 0.10 m wide with a thickness of 3.175 mm (1/8 in.) would produce 37,805 N of force with 16 magnets acting on the fin at a 3 mm air gap. This will produce a deceleration of 4.45 m/s2 or 0.454 G. This is just outside the 0.45 G limit, but still deemed acceptable especially for this extreme case.

There will be eight magnets on each side of the brake. Each magnet will be next to and facing another magnet of opposing polarity. A pole pitch (distance between magnets of the same polarity) of 150 mm will be used for this design [5]. Two different brake run layouts were considered. The first was placing an induction fin on every other roller coaster car, starting with the lead car. The second was to place an induction fin on every car of the roller coaster. Equations (3) and (4) were used to determine the deceleration of the train as each fin passes through a brake.

$$a = \frac{v_f - v_i}{\Delta t} \tag{3}$$

$$\Delta t = \frac{d}{v} \tag{4}$$

It was found that the brake run with an induction fin on every car would be best because it is 2.6 m shorter and uses 12 less brakes than the other design considered. This is also a better design when taking the cost of each brake and the track material into account. This design does have twice as many induction fins, but it can be assumed that the price of brakes is much more expensive than the aluminum fins. The velocity dropped -0.65 m/s for each fin going through a brake set. Near the end of the brake run, because the roller coaster is travelling at a relatively slow velocity, it was found that two fins could interact with two brakes without exceeding the deceleration limit. These two fins would have 32 total magnets creating eddy currents on them. After the train has slowed enough to allow the friction brakes to be implemented, the total braking distance is 53.6 m. This braking distance and how it relates to the roller coaster's velocity and deceleration are seen in Figs. 3 and 4.

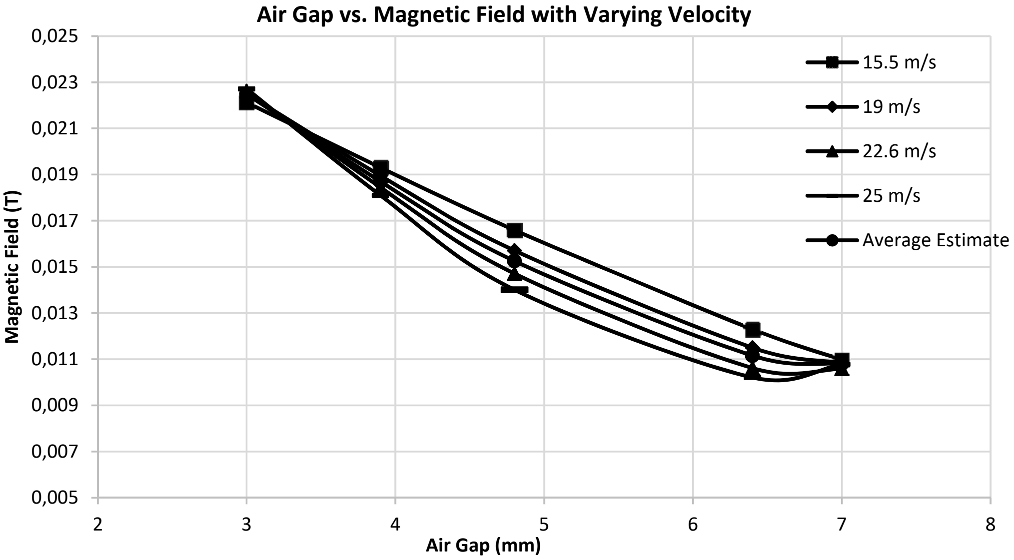

Fig. 2 Change in magnetic field with varying air gap at four different velocities. Magnetic field was estimated at 3 mm and 7 mm using polynomial estimates

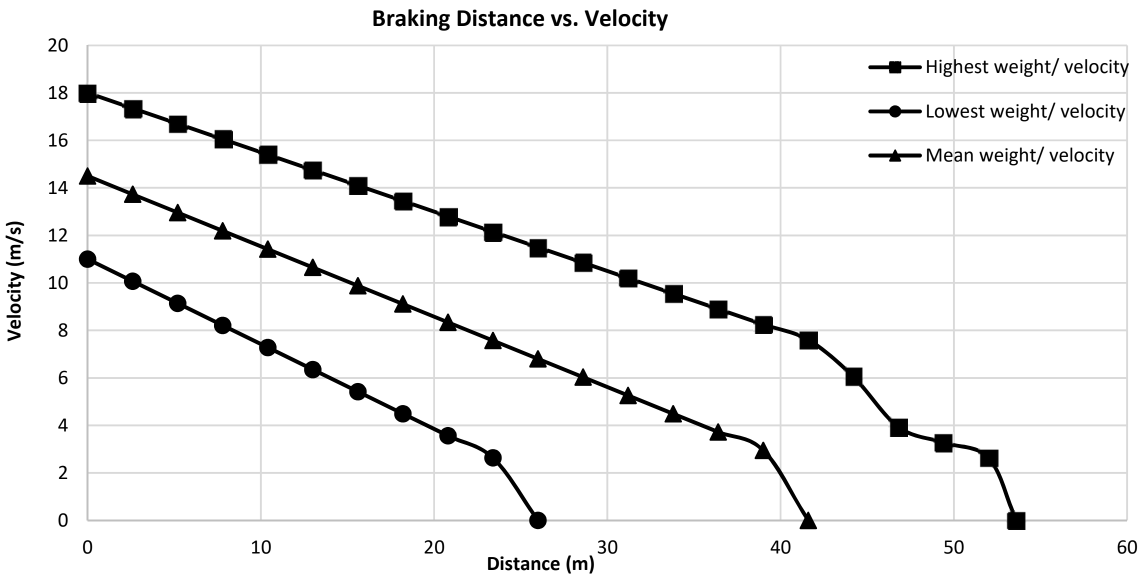

Fig. 3 Drop in velocity along the brake run for all three cases

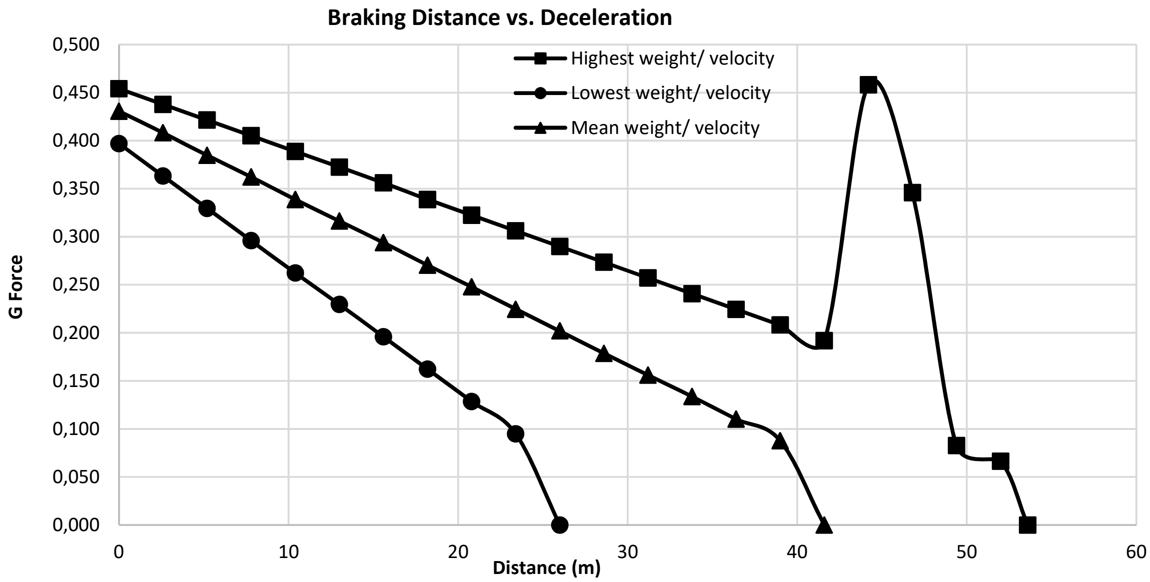

Fig. 4 Deceleration measured in G's along the brake run. The spike in the highest case is attributed to two induction fins interacting with two brakes simultaneously

VII. SUGGESTIONS FOR IMPROVEMENT AND CONCLUSION

Further work that would want to be done to improve upon this project would be to run tests similar to the ones cited in order to corroborate the results and integrate them into this design. Optimizing the magnet's size and grade would also change the brake design and the length of the brake run. In summary, a roller coaster weighing 5,938-8,496 kg and travelling 11-18 m/s would need a maximum of 53.6 m to stop. This would be with induction fins made of Al6061 that are 0.75 m long by 0.10 m wide and 3.175 mm thick. These fins will be placed on every car of the six-car train. Each brake contains 16 50 mm x 50 mm x 12 mm N35 magnets, with three brakes making one set. There is a total of four brake sets, with the last one placed for the most extreme case of speed and weight, but can remain there for the sake of redundancy. These specifications should theoretically meet the maximum 0.45 G deceleration that is required. Although this design was converged upon using theoretical calculations, it can be assumed that it stays within the realm of feasibility.

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