# MAGNETIC TRAIN

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**A B S T R A C T**

**M**agnetic train as one of the IYPT 2016 problems contains a battery with two attached permanent magnets in both ends of it; when put in solenoid it moves. Why this train moves and relevant parameters have been studied to find its best efficiency and the effect of some relevant parameters on speed and power with considering electromagnetic laws. Using simulation and formulas help to study more on magnetic fields in the whole train.

## 1 Introduction

The theory discussed in this paper is around the battery with two permanent magnets that attached to the both ends of the battery. When you put them in a copper coil will be moved through the solenoid.

Will Robertson *et al*., worked about calculating axial force between a coaxial cylindrical magnet and a thick coil (a solenoid that its thickness should considered and isn't negligible ) with relative displacement in axial direction. This theory is in both theoretical and analytical type with two different way of calculating and formulas [1].

## 2 Theory

For two circular coaxial loops (i.e., a single turn of a solenoid) carrying currents, the axial force between them is given by:

$$F_f(r_1, r_2, z) = \mu_0 I_1 I_2 z \sqrt{\frac{m}{4 r_1 r_2}}$$
$$\times \left[ K(m) - \frac{m/2 - 1}{m - 1} E(m) \right] \quad (1)$$

$$m = \frac{4 r_1 r_2}{[r_1 + r_2]^2 + z^2} \quad (2)$$

Where $r_1$ and $r_2$ are the coil radii z and is the axial distance between them. The functions $K(m)$ and $E(m)$ are the complete first and second elliptic integrals respectively with parameters. These functions can also be referred to with notation $K(k)$ and $E(k)$ in terms of a modulus $k_1$ where $m = k^2$. Using the "filament method," (1) and (2) can be used to calculate the force between any arrangement of coaxial solenoids by representing each turn of the solenoid as a separate coil, and summing the forces through superposition for every pair-wise combination of coil interaction forces.

$$F_{z_1} = \sum_{n_m=1}^{N_m} \sum_{n_r=1}^{N_r} \sum_{n_z=1}^{N_z} F_f(r(n_r), R_m, z + L(n_m, n_z)) \quad (3)$$

$$r(n_r) = R_c + \frac{n_r - 1}{N_r - 1}[R_c - r_c] \quad (4)$$

$$L(n_m, n_z) = -\frac{1}{2}[l_m + l_c] + \frac{n_z - 1}{N_z - 1} l_c + \frac{n_m - 1}{N_m - 1} l_m \quad (5)$$

where $R_m$ is the magnet radius , $r_c$ and $R_c$ are the inner and outer coil radii,  lm and lc are the magnet and coil lengths, $z$ is the axial distance between their centers, $N_r$ and $N_z$ are the number of turns in the thick coil in the radial and axial direction, and $N_m$ is the number of turns in the thin coil.

Flexible algorithm is calculated for accurate computation of off-axis magnetic fields of coil in cylindrical geometry (Robert H. Jackson *et al.*).

This calculation was about a partial power series decomposition of Laplace's equation about the symmetry axis where the series coefficients are derivatives of field along the axis and computed for basic coil type (loop, annular disc, thin solenoid, full coil) with high order analytic derivatives [2] and the general vector field inside a real (finite) solenoid has been studied by: (R. Muniz *et al.*, 2015) (Fig. 1)[3].
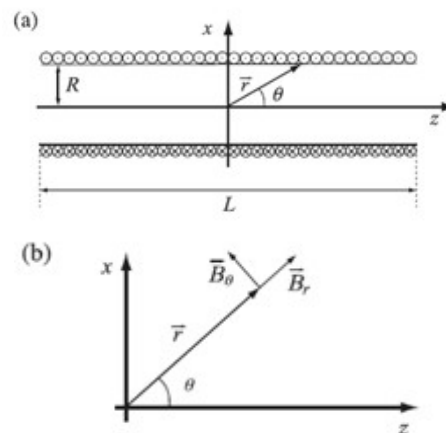


**Fig. 1:** The  vector field inside a real (finite) solenoid

$$B_\rho \simeq \frac{3\alpha L R^2 r^2}{2(R^2 + L^2/4)^{5/2}} \sin\theta \cos\theta. \quad (6)$$

Finally, using q ¼ r sin h and z ¼ r cos h :

$$B_\rho(\rho, z) \simeq \frac{96\pi NI}{c}\left(\frac{R^2 z \rho}{L^4}\right), \qquad (7)$$

Here, we introduced a magnetic train moves in a solenoid and surveyed the relevant parameters and measured its velocity and power too.

## 3 Material and Methodology

Because of the current in wire there is a magnetic field around it. In our setup the permanent magnet and the battery produce current in solenoid. When a current passes from the solenoid a magnetic field is produced in and around of it and with right hand rule, the north and south poles will be set. If the opposite poles of permanent magnets are outwards, the poles will attract the opposite pole of the solenoid so the vectors of magnetic force will be in opposite direction and its resultant vector will be zero (Fig.2).
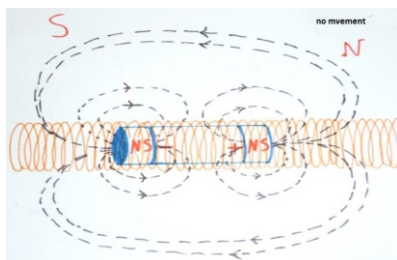


**Fig. 2.** :The fields of train when there is no movement

But if the same poles of permanent magnets are outwards; one of the poles will attract the opposite pole of the solenoid's field and another pole repulse the same pole of it so the vectors of magnetic force will be in the same direction and it's resultant vector will not be zero. It means that just if same poles of magnetic train are outwards the interaction of these three fields is in a way that train moves (Fig. 3).
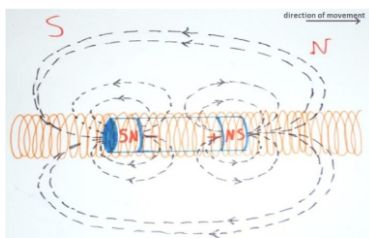


**Fig. 3 :** The fields of train in a correct way that moves

and it is important to realize that the solenoid is a thick coil with the fields in it. Until going the battery out of solenoid, there is a field around it and make a continuous movement for train (Fig.4).
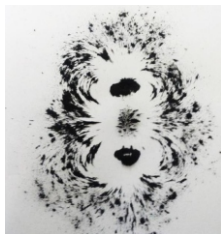


**Fig. 4:** Field of battery with its attached magnet

There is a force that reduces the speed of train or sometimes makes it stop. There is some spaces between wires of solenoid when the train moves through the solenoid and passes these spaces, the edge of train sticks in this spaces. A force perpendicular on the wire and the edge of train avoids train from movement (Fig. 5).
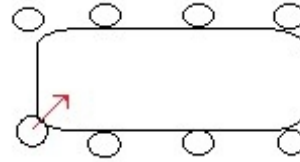


**Fig. 5.:** The direction of the force that reduces the speed of train on the edge of train

## 4 Experiments

The set up in our experiments has been built with four thin threads that make the length of solenoid constant, two short cardboards in both sides of solenoid to avoid shaking and a paperboard under it to avoid make any contact with other conductive surface, 9 disc magnets and two types of battery: NiMH rechargeable battery and alkaline (Fig. 6).
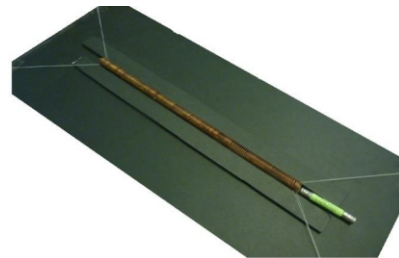


**Fig. 6:** experimental set up

According to electromagnetism laws the force between two magnets are measured .

There is an inducted field in solenoid as a permanent cylindrical magnet. The force between two magnets are equal to force between an iron and a magnet [4] so the force between magnet that attached to battery with battery is equal to the force between two magnets. To make the train move we must attach four or five disc magnet to each other because they aren't powerful enough lonely so they behaves like a cylindrical magnet that force between them and the solenoid is measured (Eq. 8) [4,5,6]:

$$F(x) = \frac{\pi\mu_0}{4}M^2 R^4 \left[\frac{1}{x^2} + \frac{1}{(x+2h)^2} - \frac{2}{(x+h)^2}\right] \qquad (8)$$

Where M is the magnetization of the magnets and x is the distance between them. However, we have an attraction and repulsion, too; that is measured with (Eq. 9).

$$F = \frac{\mu q_{m1} q_{m2}}{4\pi r^2} \qquad (9)$$

Where F is force, $q_{m1}$ and $q_{m2}$ are the magnitudes of magnetic poles , μ is the permeability of the intervening medium , r is the separation .

## 5 Simulation

As it mentioned before; our solenoid is a thick coil because the current just passes around the train, so the magnetic field just inducted around the train, not in the whole solenoid. The field in solenoid is less homogenous

density in the thick coil is more than around of it; so the speed of train inside the solenoid is more . We put the train in the solenoid and simulated the thick coil's magnetic field using COMSOL Multiphysics. The simulation is in elementary steps and the whole train will simulated in future (Figures 7 and 8).
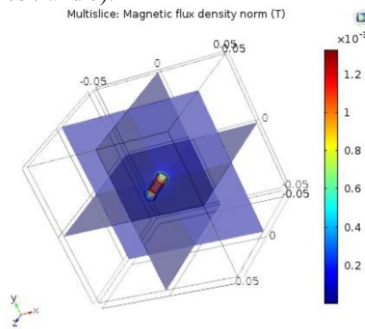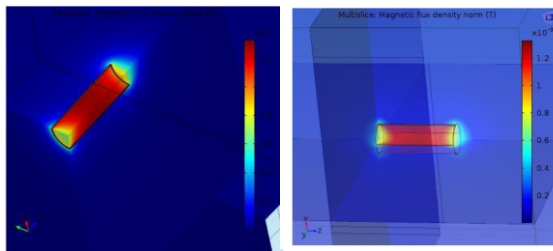


**Fig. 7:** outlook of simulation



**Fig.8:** closeup of the magnetic field of the thick coil

The compression of wires in the solenoid is 5.413±0.05 mm in each centimeter. Material of solenoid is copper because it has high electric conductivity. The thickness of wire is 1.16±0.005 mm and internal diameter of solenoid is 13.42±0.005 mm (tables 1 and 2).

**Table 1** : Batteries are used in our experiments

| battery | Thickness (mm) | Length (mm) | Internal resistance (Ω) |
|---|---|---|---|
| (alkaline) | 10±0.05 | 42±0.05 | 1.02±0.005 |
| (NiMH) | 10±0.05 | 43±0.05 | 0.84±0.005 |

**Table 2** : Magnetic fields, measurements with magnetometers software

| magnet | Magnetic field(μT) | Thickness (mm) | Radius(mm) | number |
|---|---|---|---|---|
| | 855±0.1 | 4±0.05 | 5±0.05 | 1 |
| | 560±0.1 | 2±0.05 | 5±0.05 | 1 |
| | 1012±0.1 | 5±0.05 | 5±0.05 | 2 |
| | 653±0.1 | 3±0.05 | 5±0.05 | 5 |

## 6 Results

The experiments and all results are shown in the following figures. By increasing current; speed increases, too (Fig. 9).
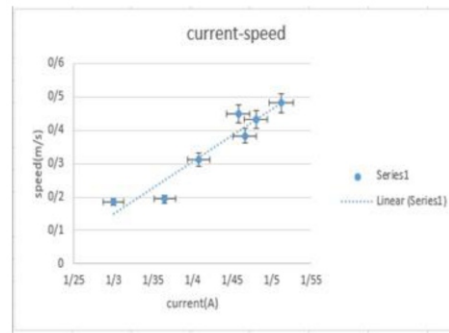


**Fig. 9:** the speed versus current with alkaline battery

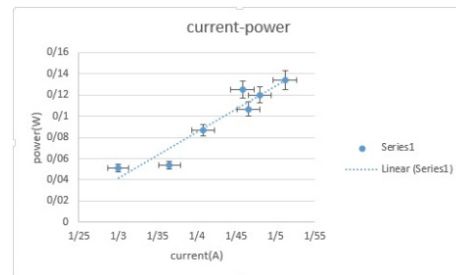By increasing current, power increases, too (Fig. 10).



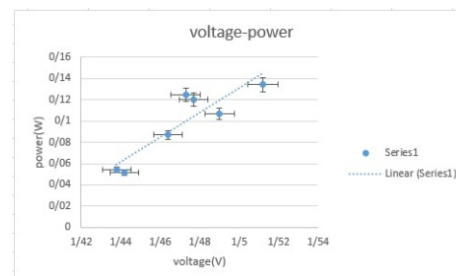**Fig. 10:** power versus current with alkaline battery



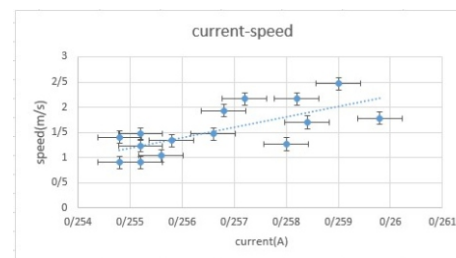**Fig. 11:** power versus voltage with alkaline battery



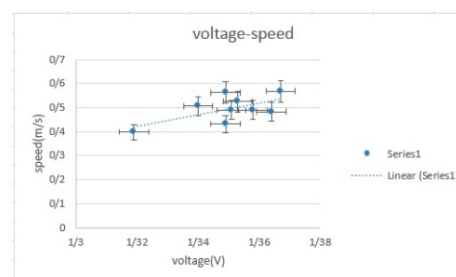**Fig.12:** Speed versus current with NiMH battery



**Fig.13:** Speed versus voltage with NiMH battery

According to these charts and formulas, the relations between these parameters are linear. By increasing voltage and current, power and speed will increase, too.

For better efficiency, we can use batteries with higher voltage and current, less mass and make the solenoid smooth to avoid forces that decrease the speed.

## 7 Conclusion

Magnetic train moves with magnets attached to the battery from the same poles and in a copper coil. It is better to put train in the solenoid because the magnetic flux density is more in the solenoid than around of it . Our solenoid is a thick coil because the field is inducted just around the battery and moves with it through the solenoid that helps train to move along the whole solenoid. Every parameter that makes the fields powerful can improve efficiency. As shown in figures, with increasing voltage and current; power and speed increases too and there is a linear relation between them. For increasing efficiency, the easiest way is increasing current because it has most effect to make the field of coil powerful.

References

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