Experiment 4

Magnetic Forces

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1 Introduction

In this experiment, we measure the forces on magnetic material from a strong permanent magnet, which has an inhomogeneous magnetic field. From the force measurements, we are able to determine the type of magnetic material. All materials fall into one of three magnetic classes. Diamagnetic materials are weakly repelled by strong external magnets and paramagnetic materials are weakly attracted regardless of the direction of the field, and quickly lose any magnetic moment when the external field is removed. Ferromagnetic materials are either 'soft' or 'hard'. Soft ferromagnets develop a large net magnetic moment when an external field is applied but like paramagnetic and diamagnetic materials, the moment does not persist if the field is removed. Hard ferromagnets retain a permanent magnetic dipole moment, even in the absence of an external field. They can be strongly attracted, repelled and torqued by other magnets, depending on orientation. We chose to measure the forces of a strong rare earth neodymium magnet (a hard ferromagnet) acting on another hard ferromagnet, and a soft ferromagnet (a Canadian nickel).

We expect the force-distance power law for the main types of magnetic materials to be in the following format where z is the distance between the materials:

$$|F_m| = \frac{C}{z^n}, \qquad n = 4 \; or \; n = 7, \quad C = some \; constants \tag{1}$$

This relation is explored more deeply in the Discussions section. For hard ferromagnetic samples, an inverse 4^{th} power law is predicted ($n = 4$), while for soft ferromagnets, and paramagnetic and diamagnetic materials, an inverse 7^{th} power law is predicted. By analyzing the magnetic force of a strong neodymium magnet on our samples at various distances, we experimentally confirm that a Canadian nickel is a soft ferromagnetic material, while a common fridge magnet is a hard ferromagnetic material.

2 Experimental Method

List of Equipment:

- Milligram-sensitice electronic balance
- Strong rare-earth neodymium magnet
- Apparatus to hold strong rare-earth magnet at fixed distances
- Fridge magnet
- Canadian Nickel
- 2 red Solo cups
- Tape

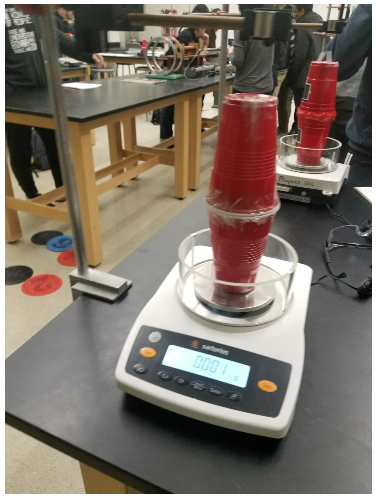

Figure 1: Apparatus used for experiment, along with the electronic balance

The experimental setup, as shown in Figure 1 is as follows: Solo cups taped together are placed on the electronic balance, and the balance is tared to calibrate its measurement such that the weight of the cups is not measured. (i.e. only the weight of our specimens are measured.) For both magnetic materials, an initial reading of the specimen's weight is taken, which is placed on top of the cups. The arm is raised as high as possible to keep the strong rare-earth magnet as far away as possible from the specimen, because at close distances, the reading on the scale will be skewed, due to the magnetic field of the strong rare-earth magnet. Then, several measurements are recorded at various distances as the rare-earth magnet is moved towards the specimen, since the magnetic field of the rare-earth magnet interacts with the specimen and changes the weight measured by the scale. The readings on the scale are converted into Newtons, and the distances measured are from the bottom of the rare-earth magnet to the top of the specimen, measured in metres.

3 Results

The raw data recorded for the fridge magnet as a specimen are as follows:

distance z (m)	balance reading (g)	$\lvert F_m\rvert$ (N)	$\ln(z)$	$\ln(\lvert F_m\rvert)$
0.494	15.863	3.92399999999957E-05	-0.705219761794215	-10.1458139232672
0.347	15.87	0.00010791	-1.05843049903528	-9.1342130115887
0.29	15.879	0.0001962	-1.23787435600162	-8.53637601083303
0.267	15.887	0.00027468	-1.32050662058189	-8.19990377421178
0.249	15.896	0.00036297	-1.39030238251743	-7.92119037174276
0.234	15.903	0.00043164	-1.45243416362444	-7.74791865046873
0.209	15.917	0.00056898	-1.56542102701733	-7.47166527384059
0.199	15.931	0.00070632	-1.61445045425764	-7.25544216537096
0.194	15.939	0.0007848	-1.63989711991881	-7.15008164971312
0.189	15.948	0.00087309	-1.66600826392249	-7.04347191465486
0.184	15.953	0.00092214	-1.69281952137315	-6.988813502117
0.179	15.963	0.00102024	-1.72036947314138	-6.88771738524564
0.169	15.987	0.00125568	-1.77785656405906	-6.68007802046738
0.159	16.02	0.00157941	-1.83885107676191	-6.45070391940254
0.154	16.038	0.00175599	-1.87080267656851	-6.34472247854625
0.149	16.06	0.00197181	-1.90380897303668	-6.22880337632793
0.144	16.087	0.00223668	-1.93794197940614	-6.10276265543256
0.139	16.116	0.00252117	-1.97328134585145	-5.98303219949178
0.134	16.15	0.00285471	-2.00991547903123	-5.85878501721551
0.129	16.189	0.0032373	-2.04794287462046	-5.73301562992648
0.124	16.243	0.00376704	-2.0874737133771	-5.58146573179928
0.119	16.299	0.0043164	-2.12863178587061	-5.4453335574747
0.114	16.373	0.00504234	-2.17155683058764	-5.28988501893184
0.109	16.453	0.00582714	-2.21640739675299	-5.14522896502436
0.104	16.557	0.00684738	-2.26336437984076	-4.98388918162463
0.099	16.682	0.00807363	-2.31263542884755	-4.81915208370993
0.098	16.708	0.00832869	-2.32278780031156	-4.78804909807566
0.097	16.734	0.00858375	-2.33304430047875	-4.75788439802939
0.096	16.769	0.0089271	-2.3434070875143	-4.71866368487611
0.095	16.8	0.00923121	-2.3538783873816	-4.68516514480162
0.094	16.84	0.00962361	-2.36446049671213	-4.64353582482164
0.093	16.87	0.00991791	-2.37515578582888	-4.61341306536653
0.092	16.904	0.01025145	-2.3859667019331	-4.58033611998809
0.091	16.948	0.01068309	-2.39689577246529	-4.53909316145404
0.09	16.988	0.01107549	-2.40794560865187	-4.50302072023734
0.089	17.038	0.01156599	-2.41911890925	-4.45968638384963
0.088	17.071	0.01188972	-2.43041846450393	-4.43208111775774
0.087	17.11	0.01227231	-2.44184716032755	-4.40040977392009
0.085	17.208	0.01323369	-2.46510402249182	-4.32498942817925
0.082	17.372	0.01484253	-2.50103603171788	-4.21025857059865
0.079	17.57	0.01678491	-2.53830742651512	-4.08727501049481
0.074	17.973	0.02073834	-2.60369018577797	-3.87577111795682
0.064	18.888	0.02971449	-2.74887219562247	-3.51612047335976
0.054	20.578	0.04629339	-2.91877123241786	-3.07275609266061

Table 1: Measurements of force on the electronic balance with the rare-earth magnet and the fridge magnet at various distances

Sample calculation of converting balance reading to force:

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balance reading: 15.863g

$$|F_m| = 15.863g \times \frac{1kg}{1000g} \times 9.81\,\mathrm{m/s^2} = 3.923\,999\,999\,999\,57 \times 10^{-5}\,\mathrm{N}$$

A linear graph is produced by plotting the natural logarithm of distance from rare-earth magnet to fridge magnet vs. the natural logarithm of the force measured by the balance. i.e. we plot $\ln(z)$ on the x-axis and $\ln(|F_m|)$ on the y-axis to obtain Figures 2 and 3. From Equation 1, we can easily see that the slope corresponds to the value -n as follows:

$$|F_m| = \frac{C}{z^n}$$

$$\ln(|F_m|) = \ln\left(\frac{C}{z^n}\right)$$

$$\ln(|F_m|) = -n\ln(z) + ln(C)$$

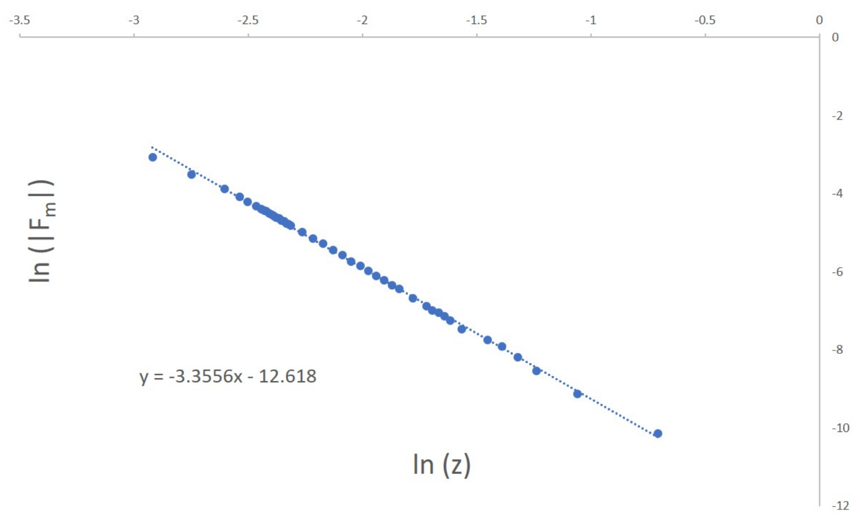

Figure 2: Natural logarithm of distance from rare-earth magnet to fridge magnet vs. natural logarithm of the force measured by the balance

Using Excel's LINEST function, we obtain the following data from the graph in Figure 2:

$$Slope = -3.35557684075733 \pm 0.018881754523524$$

Thus, we conclude $n = 3.36 \pm 0.02$. Since the fridge magnet is a permanent magnet, it is a hard ferromagnetic material, and n is expected to be 4.

Next, the raw data recorded for the Canadian nickel as the specimen is as follows:

distance z (m)	balance reading (g)	$\lvert F_m \rvert$ (N)	$\ln(z)$	$\ln(\lvert F_m \rvert)$
0.113	3.948	-3.924E-05	-10.1458139232671	-2.1803674602698
0.093	3.942	-9.80999999999979E-05	-9.22952319139298	-2.37515578582888
0.083	3.937	-0.00014715	-8.82405808328478	-2.48891467118554
0.073	3.912	-0.0003924	-7.84322883027307	-2.61729583783375
0.063	3.857	-0.00093195	-6.97823139278646	-2.7646205525906
0.058	3.793	-0.00155979	-6.46320408216677	-2.84731226843572
0.056	3.753	-0.00195219	-6.23880345966251	-2.88240358824699
0.055	3.731	-0.00216801	-6.13394558286925	-2.90042209374967
0.054	3.698	-0.00249174	-5.99477401736847	-2.91877123241786
0.053	3.665	-0.00281547	-5.87262606862738	-2.93746336543002
0.052	3.635	-0.00310977	-5.77320651050972	-2.95651156040071
0.051	3.589	-0.00356103	-5.63770545012215	-2.97592964625781
0.05	3.537	-0.00407115	-5.5038297641563	-2.99573227355399
0.049	3.486	-0.00457146	-5.38792265026136	-3.01593498087151
0.048	3.424	-0.00517968	-5.26301200068074	-3.03655426807425
0.047	3.347	-0.00593505	-5.12687982635616	-3.05760767727208
0.046	3.268	-0.00671004	-5.00415036676445	-3.07911388249304
0.045	3.168	-0.00769104	-4.86769926403659	-3.10109278921182
0.044	3.052	-0.008829	-4.72971352106269	-3.12356564506388
0.043	2.9	-0.01032012	-4.57365989108935	-3.14655516328857
0.042	2.738	-0.01190934	-4.43043231276756	-3.17008566069877
0.041	2.547	-0.01378305	-4.28431570261916	-3.19418321227783
0.04	2.312	-0.0160884	-4.12965676356876	-3.2188758248682
0.039	2.042	-0.0187371	-3.97724976334633	-3.24419363285249
0.038	1.726	-0.02183706	-3.82414675255151	-3.27016911925575
0.037	1.349	-0.02553543	-3.66768837939244	-3.29683736633791
0.036	0.86	-0.03033252	-3.49553487467969	-3.32423634052603
0.035	0.237	-0.03644415	-3.31197432723514	-3.35240721749272

Table 2: Measurements of force on the electronic balance with the rare-earth magnet and the Canadian nickel at various distances

The graph is also produced in the exact same way as before with the fridge magnet specimen:

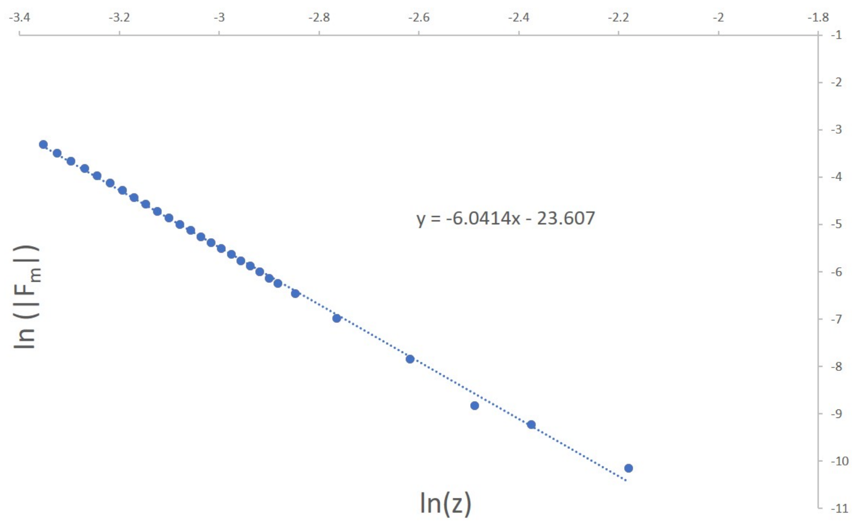

Figure 3: Natural logarithm of distance from rare-earth magnet to Canadian nickel vs. natural logarithm of the force measured by the balance

Using Excel's LINEST function, we obtain the following data from the graph in Figure 3:

$$Slope = -6.04142520404573 \pm 0.055033493756539$$

Thus, we conclude $n = 6.04 \pm 0.06$. Since the nickel does not produce its own magnetic field, but is strongly attracted to hard ferromagnetic material, it is a soft ferromagnetic material, and n is expected to be 7.

4 Discussion

From our results, we were able to clearly classify the magnetic materials as either soft ferromagnetic or hard ferromagnetic. With experimentally determined values of 3.36 ± 0.02 for the fridge magnet, and 6.04 ± 0.06 for n in Equation 1, we clearly see that the inverse power law relation for the magnetic force as a function of distance acting on the Canadian nickel falls off quite faster than the magnetic force on the fridge magnet. This implies that the nickel is the soft ferromagnetic material, while the permanent fridge magnet is the hard ferromagnetic material. However, our experimentally determined results do not agree within error of the expected values. For hard ferromagnetic samples, an inverse 4^{th} power law is expected, while for soft ferromagnets, is expected. Although our results did not agree within error of the expected values, the graphs both fit linear curves, with no noticeable anomalous data points relative to the trendlines. This implies the source of error was constant, which can likely be attributed to a combination of the following: While attempting to measure the weights on the balance, the readings fluctuated which made it difficult to measure accurately. It is also likely that human error was introduced from measuring the distances, and/or not having the strong rare-earth magnet's center directly align with the magnetic specimens' centres even though we tried to minimize these sources of error.

As mentioned before, in Equation 1, C is a bunch of constants, and z is raised to the power of either 4 or 7 depending on the type of magnetic material. For hard ferromagnetic materials, Equation 1 is more completely represented by:

$$F_z = \pm \frac{3 m_s \mu_0 m_m}{2\pi} \frac{1}{z^4} \tag{2}$$

,where m_s is the dipole moment on the sample hard ferromagnet, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$ is the magnetic permeability of free space, m_m is the dipole moment from the strong rare-earth magnet, and z is the distance between the two magnets, in metres.

For soft ferromagnetic materials, and paramagnetic and diamagnetic materials, Equation 1 is more completely represented by:

$$F_z = \frac{3 \mu_0 \chi V m_m}{2\pi^2} \frac{1}{z^7} \tag{3}$$

,where V is the volume of the sample material.

The sign of χ:
To obtain our graphs in Figures 2 and 3, Equation 1 was linearized to obtain:

$$\ln(|F_m|) = -n \ln(z) + ln(C)$$

The magnetic susceptibility χ is positive or negative, depending on the material, which determines if the magnetic force is attractive or repulsive. For by observing the equation our graph is based on above, C had to be positive, or it would have been impossible to obtain the natural logarithm $\ln(C)$. Therefore, in Equation 3, χ must be positive, in order for C to be positive. This is further reinforced by the observation that the magnetic force is attractive when the strong magnet gets close to the nickel, as the nickel would stick to the rare-earth magnet very strongly if the magnet got too close.

5 Conclusions

In Experiment 4, we measure the forces on magnetic material from a strong permanent magnet at varying distances. From the force measurements, we were able to classify the type of magnetic material (soft or hard ferromagnetic). The specimens were a fridge magnet, and a Canadian nickel, which are a hard ferromagnetic material and soft ferromagnetic material, respectively. The force-distance relation for the fridge magnet was expected to have an inverse 4^{th}

power law, and the experimentally obtained value was 3.36 ± 0.02. An inverse 7^{th} power law was expected for the nickel, and the experimentally obtained value was 6.04 ± 0.06. While the values do not agree within error, it is easy to see that the soft ferromagnetic material (the nickel) had a inverse power law falloff significantly faster than the hard ferromagnetic material (the fridge magnet), which is what was expected of the experiment. Errors in the experimentally determined value can be attributed to the electronic balance's measurements fluctuating, and human error in measuring the distances. Overall, the graphs fit the linear trend that was expected, and while the results do not agree within error, we were still able to classify the magnetic materials correctly.