Forces in Permanent Magnets

Team Workshop Problem 23

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General:
This problem is intended to address the questions of force calculations as well as modeling of permanent magnets in axisymmetric and three dimensional geometries.

Measurements:
The measurements presented here were performed as part of a design process followed by computation of forces to confirm the design. The measurements consist of axial and restoring forces for two configurations, both involving small magnets and coils. One configuration uses Samarium-Cobalt the other, Neodymium-Iron-Boron magnets. Two sizes of magnets and coils are used in each configuration.
The magnet and coil are shown in Figure 1. The coil is wound on a nonmagnetic form (brass in this case) with dimensions given in Table 1 for both configurations. The only differences between the configurations is in dimensions and type of magnets.

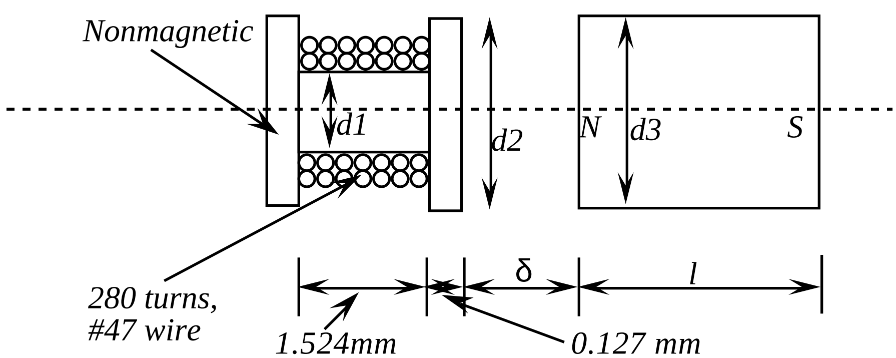

Figure 1. Configuration for axial force measurement and dimension. δ varies between 0 and 0.6526mm, nominal is 0.33mm.

Table 1. Dimensions for the two configurations studied.

Configuration	d_1	d_2	d_3	l	coil res.	wire length
A	3.048	3.9624	2.9972	1.6	57Ω	3m
B	1.524	3.175	1.6	0.8128	32Ω	1.68m

A Samarium Cobalt, B Neodymium Iron Boron

Notes:
Small magnet is a cylindrical magnet 0.8128mm long and 1.6mm in diameter.
Large magnet is a cylindrical magnet, 1.6mm long and 3mm in diameter
The small coil is 1.524mm long, cylindrical, with inner diameter 1.524mm. 280 turns of #47 wire is wound on the inner core to form a cylindrical coil.
The large coil is 1.524mm long, cylindrical, with inner diameter 3.048mm. 280 turns of #47 wire is wound on the inner core to form a cylindrical coil.

Configuration A:. Samarium-Cobalt magnet and larger coil.

In measuring axial forces, the coil and magnet remain co-axial. In measuring restoring force, the magnet and coil move sideways with their axes parallel (see Figure 2). There is no twisting. In both axial and restoring force measurements, the magnet and coil were in repulsion mode.

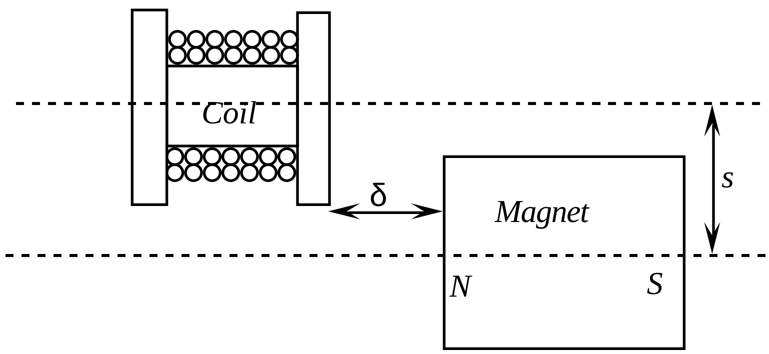

Figure 2. Restoring force: The magnet is moved sideways while keeping its axis parallel to that of the coil.

The following forces were measured.

Table 2. Forces as a function of current in coil at fixed distance between magnet and coil. Axial force between magnet and as a function of current at δ=0.254mm, magnet and coil are coaxial.

Current in coil (mA)	Force between small magnet and small coil ($N \times 9.81 \times 10^{-3}$)	Force between large magnet and large coil ($N \times 9.81 \times 10^{-3}$)
0	0	0
10	0.048	0.226
20	0.095	0.453
30	0.143	0.682
40	0.189	0.908
50	0.236	1.132
60	0.282	1.360
70	0.331	1.587
80	0.377	1.815
90	0.425	2.043
100	0.472	2.269

Table 3. Axial force between magnet and coil as a function of axial displacement at a fixed current of 50mA. Magnet and coil are coaxial.

Axial displacement δ (mm)	Force between small magnet and small coil ($N \times 9.81 \times 10^{-3}$)	Force between large magnet and large coil ($N \times 9.81 \times 10^{-3}$)
0	0.3758	1.4617
0.014	0.366	1.440
0.034	0.352	1.409
0.054	0.339	1.382
0.074	0.326	1.354
0.094	0.314	1.326
0.114	0.303	1.301
0.134	0.292	1.273
0.154	0.281	1.248
0.174	0.271	1.223
0.194	0.262	1.198
0.214	0.253	1.174
0.234	0.244	1.150
0.254	0.236	1.129
0.274	0.227	1.106
0.294	0.219	1.084
0.314	0.213	1.063
0.334	0.205	1.044
0.354	0.197	1.025
0.374	0.192	1.004
0.394	0.185	0.986
0.414	0.178	0.967
0.434	0.173	0.951
0.454	0.166	0.934
0.474	0.161	0.917
0.494	0.156	0.901
0.508	0.1525	0.8898
0.514	0.151	0.885

Table 4. Restoring force between magnet and coil as a function of side displacement at a fixed current of 50mA. Displacement is measured between the axes of the coil and magnet.

Side displacement *s* (mm)	Force between small magnet and small coil ($N \times 9.81 \times 10^{-3}$)	Force between large magnet and large coil ($N \times 9.81 \times 10^{-3}$))
0	0	0
0.020	0.001	0.014
0.040	0.003	0.031
0.060	0.006	0.044
0.080	0.010	0.059
0.100	0.015	0.074
0.120	0.019	0.087
0.140	0.022	0.103
0.160	0.027	0.117
0.180	0.030	0.130
0.200	0.034	0.144
0.220	0.038	0.158
0.240	0.042	0.171
0.260	0.045	0.185
0.280	0.050	0.197
0.300	0.053	0.210
0.320	0.056	0.223
0.340	0.060	0.233
0.360	0.063	0.247
0.380	0.066	0.259
0.400	0.069	0.270
0.420	0.072	0.281
0.440	0.075	0.293
0.460	0.079	0.304
0.480	0.082	0.315
0.500	0.084	0.326
0.508	0.085	0.330
0.520	0.086	0.336

Configuration B: Neodymium-Iron-Boron Magnet and smaller coil.

In measuring axial forces, the coil and magnet remain co-axial. In measuring restoring force, the magnet and coil move sideways with their axes parallel. There is no twisting. In both axial and restoring force measurements, the magnet and coil were in repulsion mode.

The following forces were obtained.

Table 5. Forces as a function of current in coil at fixed distance between magnet and coil. Axial force between magnet and as a function of current at δ=0.254mm, magnet and coil are coaxial.

Current in coil (mA)	Force between small magnet and small coil ($N \times 9.81 \times 10^{-3}$)	Force between large magnet and large coil ($N \times 9.81 \times 10^{-3}$)
0	0	0
10	0.040	0.220
20	0.081	0.449
30	0.121	0.677
40	0.161	0.905
50	0.202	1.131
60	0.242	1.360
70	0.281	1.586
80	0.322	1.814
90	0.362	2.042
100	0.402	2.270

Table 5. Axial force between magnet and coil as a function of axial displacement at a fixed current of 50mA. Magnet and coil are coaxial.

Axial displacement (mm)	Force between small magnet and small coil ($N \times 9.81 \times 10^{-3}$)	Force between large magnet and large coil ($N \times 9.81 \times 10^{-3}$)
0	0.3147	1.4239
0.014	0.307	1.405
0.034	0.296	1.378
0.054	0.285	1.354
0.074	0.275	1.330
0.094	0.265	1.307
0.114	0.256	1.285
0.134	0.248	1.262
0.154	0.238	1.240
0.174	0.230	1.218
0.194	0.223	1.197
0.214	0.215	1.175
0.234	0.208	1.154
0.254	0.201	1.133
0.274	0.194	1.112
0.294	0.186	1.092
0.314	0.178	1.073
0.334	0.164	1.055
0.354	0.151	1.036
0.374	0.142	1.016
0.394	0.132	1.000
0.414	0.124	0.982
0.434	0.117	0.965
0.454	0.114	0.947
0.474	0.105	0.932
0.494	0.096	0.916
0.508	0.0939	0.9041
0.514	0.093	0.899

Table6. Restoring force between magnet and coil as a function of side displacement at a fixed current of 50mA. Displacement is measured between the axes of the coil and magnet.

Side displacement *s* (mm)	Force between small magnet and small coil ($N\times 9.81\times 10^{-3}$)	Force between large magnet and large coil ($N\times 9.81\times 10^{-3}$)
0	0	0
0.020	0.006	0.016
0.040	0.009	0.034
0.060	0.013	0.045
0.080	0.017	0.062
0.100	0.021	0.077
0.120	0.025	0.090
0.140	0.028	0.104
0.160	0.031	0.119
0.180	0.035	0.133
0.200	0.039	0.147
0.220	0.043	0.161
0.240	0.046	0.174
0.260	0.049	0.188
0.280	0.052	0.201
0.300	0.055	0.216
0.320	0.058	0.229
0.340	0.061	0.243
0.360	0.064	0.255
0.380	0.067	0.268
0.400	0.070	0.281
0.420	0.073	0.294
0.440	0.076	0.306
0.460	0.079	0.318
0.480	0.082	0.329
0.500	0.084	0.342
0.508	0.085	0.347
0.520	0.086	0.354

For computation purposes, the demagnetization curves in Figures 3 and 4 were used. These are based on data obtained from manufacturers. Although the computations we performed are close to the measured results, the demagnetization curves are not exact and are not measured for the samples for which the forces were measured. They are however the best we can provide. Should measured demagnetization curves be available in the future these will be provided.

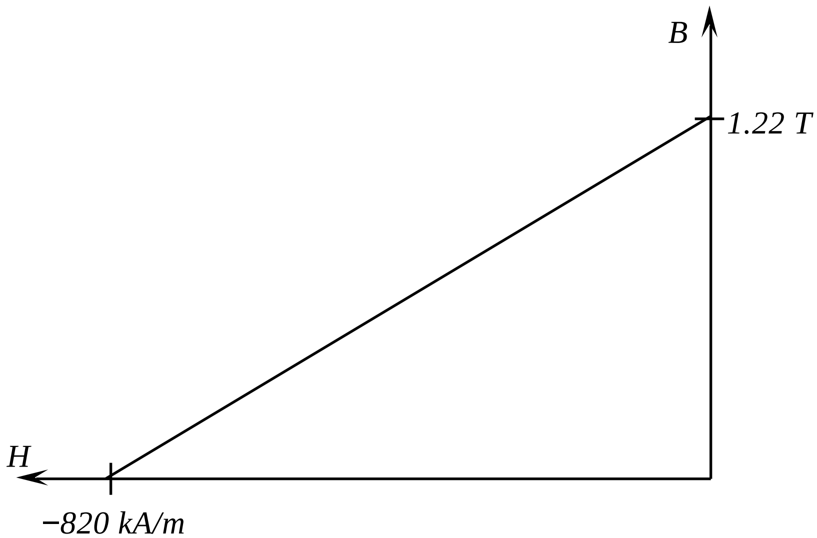

Figure 3. Demagnetization curve for Neodymium-Iron-Boron Magnets

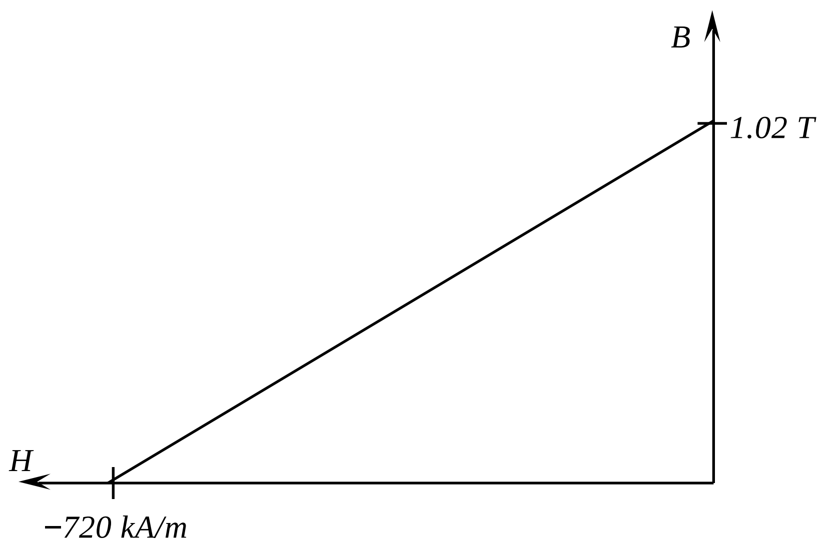

Figure 4. Demagnetization curves for Samarium-Cobalt magnets.