9. Problem №12: Rolling magnet

9.1. Solution of Australia

Problem №12: Rolling magnet

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The Problem

Investigate the motion of a magnet as it rolls down an inclined plane.

Abstract:
An investigation into the motion of a magnet as it rolls down an incline seems somewhat monotonous when first examined. However, extensive experimentation and research into this problem yields some unanticipated results. The Earth's magnetic field plays a significant role in changing the path of the magnet as it rolls down a plane. This report contains four principal investigations. First, the influence of the Earth's magnetic field on the motion of a magnet was investigated and it was found that the magnet deviates to different extents, depending on the orientation of the magnet with respect to the magnetic field. Second, the effect of varying the angle of incline was then examined. Third, the effect of changing the material of the incline was investigated using wood and aluminium ramps. Finally, further experimentation into the effect of the Earth's magnetic field's influence on neodymium magnets (super magnets), although not quantitatively analysed, showed that the magnet's strength can affect the motion of the magnet to a greater extent than the Earth's magnetic field.

1. Interpretation

1.1 Interpretation of Problem

The problem states "investigate the motion of a magnet as it rolls down an inclined plane". The Oxford English Dictionary (1) defines a magnet as "a piece of iron or steel to which the characteristic properties of loadstone have been imparted, either permanently or temporarily, by contact with another magnet, by induction, or by means of an electric current." Rolling is the "action (on the part of something) of turning over and over" (1). In the case of a cylinder, it rotates around the centre of mass. Motion is the "process of moving" or of "undergoing a change of place" (1).

1.2 Assumptions

This investigation has three principal assumptions. First, it is assumed that the magnet is cylindrical and therefore exhibits a rolling motion when released at the top of an inclined plane. Second, it is assumed that the frictional forces exhibited on the magnet during its motion are sufficient to ensure the magnet only rolls down the plane and does not exhibit a sliding behaviour. Third, it is assumed that the environment the magnet is in has little interaction with the magnet (ie. no steel beams, air resistance).

2. Theory

2.1 Motion of a cylindrical object

2.1.1 Dynamics Perspective

As the magnet rolls down the inclined plane, its magnetic field interacts with the Earth's magnetic field. The motion of the magnet down the slope is most easily analysed by breaking it into its constituent components (figure 1).

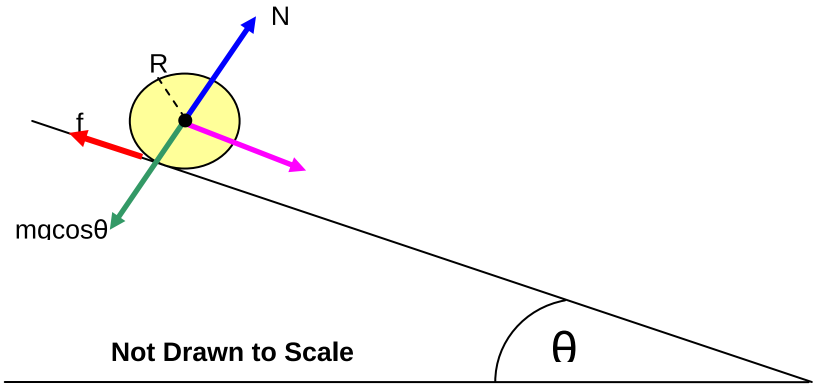


Figure 1 Components of a Rolling Cylinder

For a cylinder to roll, static friction is required. It is assumed that the static friction coefficient (μ_s) is always large enough to satisfy (2):

$$f \geq \mu_s mg\cos\theta$$

where m is the mass of the cylinder, g is acceleration due to gravity and θ is the angle. Taking this into account, the minimum static frictional force needed for rolling can be calculated

$$F = \frac{1}{3}mg\sin\theta$$

So, for a cylinder of mass 0.069kg, and an angle of 1.15° to the horizontal, the force down the plane is calculated to be 0.0045N down the plane. The translational motion of the rolling magnet along the incline was calculated (2-4)

$$F = mg\sin\theta - f = ma$$

So, for the same cylinder on the same incline, the force along the incline is 0.0090N. The rotational motion of the centre of mass (torque) was analysed (3)

$$\tau = I_{cm}\alpha$$

where α is the angular acceleration and $\alpha = \frac{a}{R}$ (3) (a is acceleration and R is the radius of the cylinder) I_{cm} is the inertia at the centre of mass. For this example, the torque calculated was 2.86 x 10-5 N around the magnet. Torque, τ, can be thought of as a force at a distance, acting to turn the magnet. The best way to calculate torque is to split it up into components (figure 2).

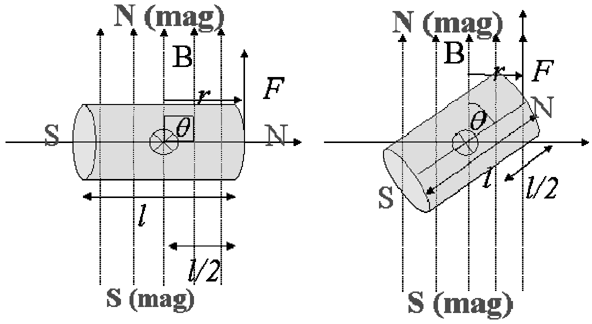


Figure 2 Components of torque for a rolling cylinder

To calculate the value of the torque, the following equation is used (4): $\vec{\tau} = \vec{r} \times \vec{F}$
where $\vec{F}$ is the force vector and $\vec{r}$ is the vector from axis of rotation to point on which $\vec{F}$ is acting.
In order to calculate the torque accurately, the restoring torque per unit of displacement was calculated. This enabled the effective work of the torque at any angle to be calculated and hence, the forces acting on the magnet. The period of oscillation was calculated

$$T = 2\pi\sqrt{\frac{I}{k}}$$

where I is the moment of inertia of the oscillating body and k is the restoring torque per unit displacement in radians. For a solid disk, such as a cylindrical magnet, the moment of inertia at the centre of mass is equal to (3)

$$I_{cm} = MR^2/2$$

Where *M* is the mass of the cylinder and R is the radius. The period of oscillation for the magnet used in the following experiments was measured by suspending it on a string and as a result, the moment of inertia for the oscillating cylindrical body. In this case, k was found to equal 4.78 x 10^{-4} Nm/radian.

2.1.2 Energy Perspective

The motion of a cylindrical object can also be analysed from an energy perspective where its initial gravitational potential energy (GPE) is converted into kinetic energy as it rolls down the incline (5)

$$mgh = \frac{3}{4}mv^2$$

Where the kinetic energy incorporates both linear and rotational kinetic energy (3)

$$\frac{1}{2}mv^2 + \frac{1}{2}I_{cm}\omega^2 = \frac{3}{4}mv^2$$

with ω representing the angular momentum of the cylinder. The velocity of the centre of mass of a sliding cylinder is (3)

$$v_{com} = \sqrt{2gh}$$

However, for a rolling cylinder, the velocity at the centre of mass is less than that of a sligin cylinder due to the potential energy being converted into both linear and rotational kinetic energy. Therefore, the velocity of the centre of mass of a rolling cylinder is (3)

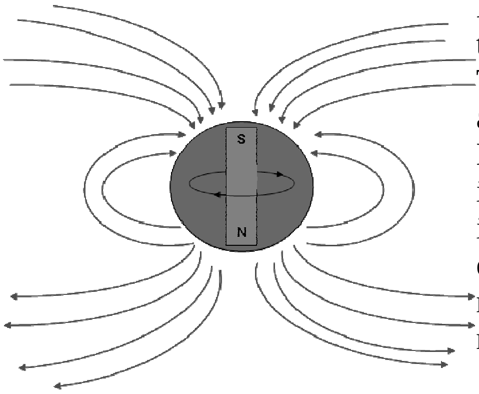
$$v_{com} = \sqrt{\frac{4}{3}gh}$$

For example, when the height of the ramp is 0.020m, the velocity at the centre of mass of a rolling cylinder is $0.511ms^{-1}$.

2.2 Effect of the Earth's magnetic field

2.2.1 The nature of the Earth's magnetic field

The Earth's north magnetic pole is located near the south geographic pole and the Earth's south magnetic pole is located near the north geographical pole (5). The angle between the Earth's north geographic pole and its North magnetic pole is called the angle of declination. Presently, this angle is approximately 10° (6). The Earth's south magnetic pole is actually the same as the south pole of a bar magnet and the Earth's north magnetic pole is actually a north pole of a bar magnet (figure 3). However, the magnetic axis is not aligned in the same position as its geographic axis. In fact, magnetic north is approximately 1000km away from geographic north (5). This is best visualised by figure 3 where the red arrows represent the Earth's magnetic field lines and the black circular arrow in the centre represents the direction of the Earth's rotation.



The angle of the Earth's magnetic field in Brisbane is about 56° to the horizontal (ground) (6) (figure 4). However, it is very weak at the surface because the surface is along way from the Earth's dipole, having a total intensity of 0.05mT (6,7). The Earth's magnetic field extends over such a large area that the strength of the magnetic field is very uniform if you look at it over a large region (7).

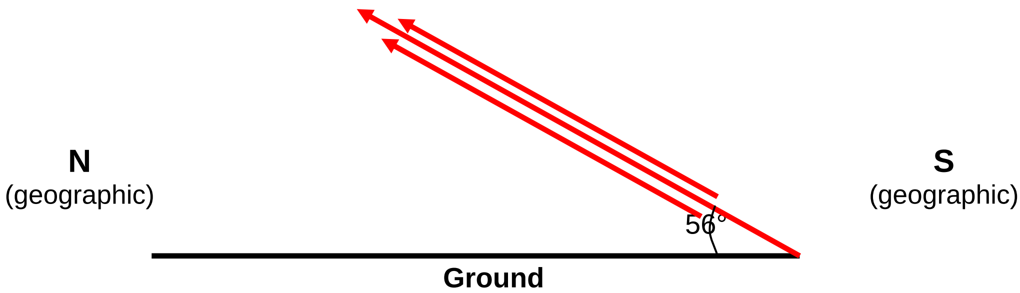


Figure 4 The Angle of the Earth's Magnetic field in Brisbane, Australia (5)

2.2.2 The effect of the Earth's magnetic field on a magnet

As a result of like poles repelling each other and unlike poles attracting each other (8), the Earth's magnetic field interacts with the rolling magnet without physical contact (9). As a magnet rolls down a plane from magnetic south to magnetic north (geographical north to south) it deviates because of interactions with the Earth's magnetic field depending on the orientation of the magnet. As a magnet rolls down a plane, its north pole will attract to the Earth's magnetic South Pole, causing it to rotate. At the same time, the magnet's South Pole is attracted to the Earth's magnetic north pole. This concept is best envisaged by examining figure 5 where the ramp is positioned so that the magnet rolls down the incline from magnetic south to magnetic north. The best way to think of this interaction in order to investigate it quantitatively is to think of the magnet and the Earth's magnetic field as two separate magnets.

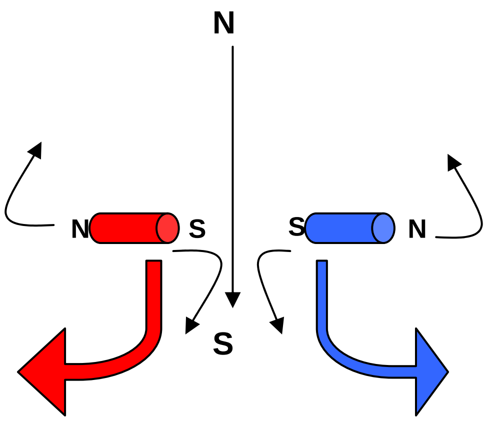


Figure 5 Effect of the Earth's magnetic field on a magnet

2.3 Aluminium

2.3.1 Eddy Currents

A cylindrical magnet has a magnetic field travelling from one pole to the other (figure 6). As the magnet rolls down the aluminium, its magnetic field cuts the aluminium sheet producing eddy currents which repel the magnet.
Eddy currents are caused by a moving magnetic field as it intersects a conductor (5). The relative motion causes a circulating flow of electrons or currents within the conductor.

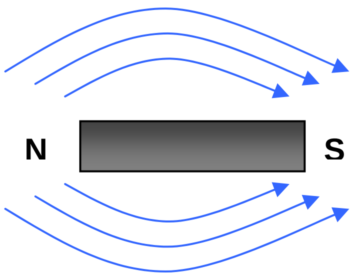


Figure 6 Eddy Currents

These circulating eddies of current create temporary electromagnets with magnetic fields that oppose the magnetic field of the magnet (figure 7).

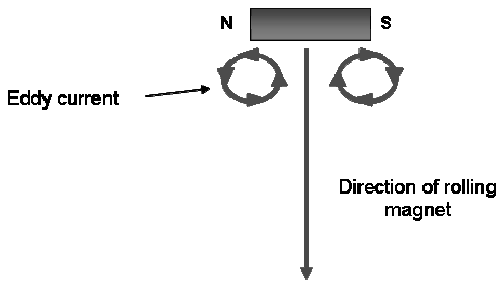


Figure 7 Eddy Currents

2.3.2 Lenz's Law

Lenz's law states that 'the current induced in a conductor by a changing magnetic field is in such a direction that its own induced magnetic field opposes the change that produced it' (5). In the case of the magnet, as it rolls down the aluminium plane, eddy currents are induced and the eddy current's own induced magnetic field opposes the change that produced it (ie. the magnet).

3. Experimental

3.1 How will varying the direction of the ramp affect the motion of the magnet?

3.1.1 Observations

The magnet was observed to deviate less at the start of the roll and deviate more near the end of the plane.

3.1.2 Results

The magnet's magnetic field strength was measured to be 36mT using a Pasco magnetic field sensor.

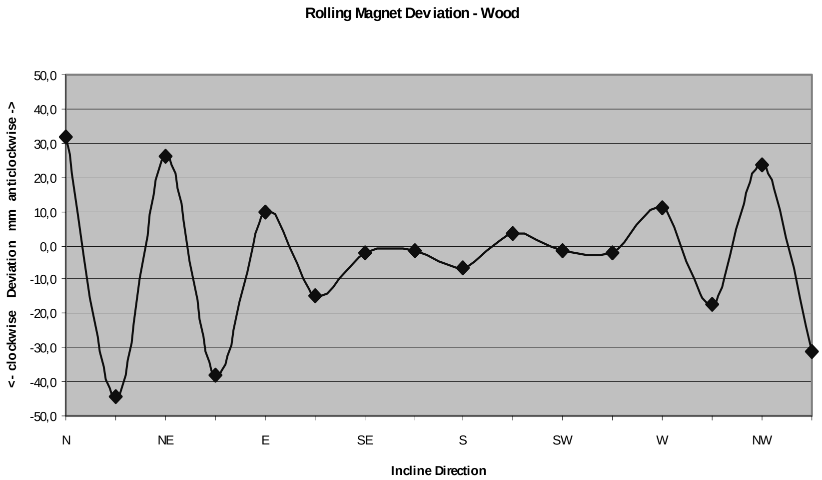
Deflection - Wood

Direction travelling	N		NE		E		SE		S		SW		W		W	
Mag N	E	W	SE	NW	S	N	SW	NE	W	E	NW	SE	N	S	NE	SW
Average	3.87	3.89	4.04	4.10	4.07	4.01	4.27	4.19	4.03	4.00	3.99	3.98	4.14	4.09	4.12	4.16
Spread	0.10	0.12	0.25	0.15	0.11	0.23	0.19	0.20	0.11	0.19	0.25	0.15	0.18	0.28	0.16	0.21
Deviation	0.06	0.07	0.17	0.08	0.07	0.14	0.12	0.12	0.06	0.11	0.18	0.08	0.09	0.20	0.11	0.11

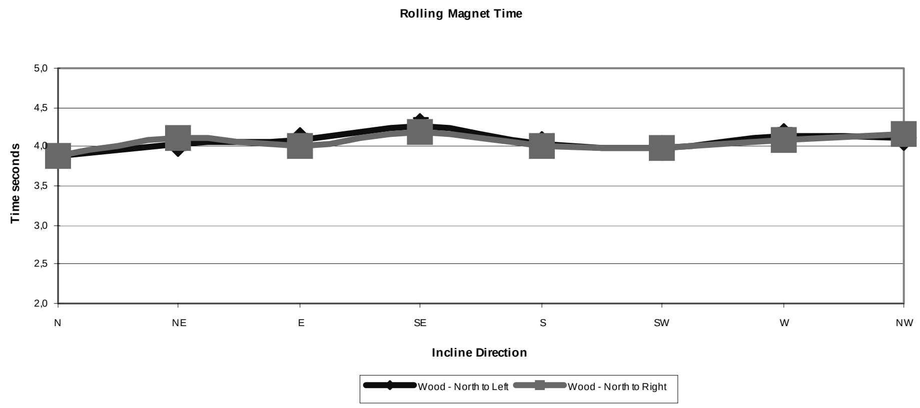
Where 'Mag N' represents the direction the north pole of the magnet points to.

Table 2 Time Results

3.1.3 Analysis of Results



This graph represents the deviation of the magnet when it rolled down the wooden plane. The two x-values for each of the magnetic directions represent the magnet's north pole facing one direction and then flipped (ie. facing east, then facing west). The negative values indicate that the magnet travelled in a clockwise direction and the positive values indicate that the magnet travelled in an anticlockwise direction.



3.1.4 Discussion

The graph indicating the deviation of the magnet as it rolls down the wooden plane shows that changing the direction of the ramp results in a change in the deviation of the magnet i.e. the deviation of a magnet is dependant on the direction of the ramp, supporting the hypothesis. Although the Earth's magnetic field only has a total intensity of 0.052mT in Brisbane, the angle of inclination of the Earth's magnetic field (56° to the horizontal) could have an effect on the magnet's motion as it rolls down the inclined plane. For example, as the magnet rolls down the ramp towards north, with its north pole facing east, the magnet deviates significantly in an anticlockwise direction. This is because the north pole of the magnet is 'north-seeking' and is therefore attracted to the Earth's magnetic north pole. However, when the magnet's north pole was facing east, and rolling in a southerly direction, the magnet only slightly deviated in an anticlockwise direction. The variation in deviation when comparing the deviation of the magnet rolling north and rolling south is attributed to the magnitude and direction of the resultant vectors produced from the Earth's magnetic field and the angle of incline of the ramp. Where the red arrow represents the direction the magnet is traveling on the ramp, at an angle of 1.15°. The blue arrows represent the inclination of the Earth's magnetic field and the dotted arrows represent the resultant vectors from each addition. This force is translated into torque and the magnet is rotated. When the magnet rolls in a southerly direction, the resultant force is nowhere near as large, as a result, little deviation occurs.

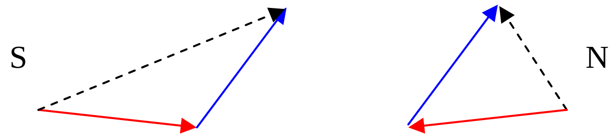
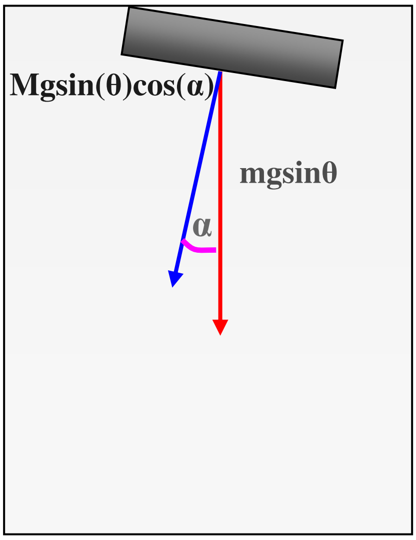


Figure 11. Resultant vectors

The increase in deviation as the magnet rolled down the plane (an observation) is attributed to it traveling at a faster speed near the end and the effect of torque. This means that friction plays less of a role in opposing the force that is turning the magnet. It also means that once the magnet has been forced slightly off its straight path, the deviation will continue to grow regardless of external magnetic forces. This deviation (excluding any external magnetic force) can be modeled by the equation $F = mg\sin\theta\cos\alpha$ and used to estimate the final position of the magnet as it rolls down the plane. In a real situation, with the external magnetic force present during the whole experiment, the deviation would be greater than calculated using this formula.



The graph of time versus direction shows, within experimental error, that the time taken for a magnet to roll down the plane with its north pole facing one direction is the same as when the magnet's north pole is facing 180° (the other direction). When the magnet was rolling north, it rolled down the ramp in the smallest time. This is probably due to the fact that the magnet is rolling down 'with' the Earth's magnetic field. This would have a resultant force with a large vector down the plane, meaning that the magnet would receive an extra 'push' of energy that it would not receive if it was traveling any other direction. The peak in time when traveling southeast is attributed to the magnet deviating the magnet in a clockwise direction for both trials.

The magnet making a moderately loud sound as it rolled down the ramp is attributed to the 15% friction between the two surfaces which was converted into heat and sound energy. Every effort was made to ensure the trials were as analogous as possible. Each time the ramp was reorientated, the magnet was placed at least twenty metres away to ensure minimal interaction. Experiments were also conducted in a wooden house on a wooden table and as far away from any steel beam supports as possible. However, it is highly likely, due to possible compass errors, that the ramp could have been misaligned by several degrees, therefore altering the results. During experimentation, the ramp was wiped down with a slightly damp cloth and left to dry every so often to try and prevent excess friction due to dust and moisture particles. In order to minimize error in timing, the person with the stop watch was the one who released the magnet. Much thought was put into deciding the most accurate process to measure the deviation of the magnet.

3.1.9 Conclusions

As the magnet rolls down the ramp, it tries to align its poles with the Earth's magnetic poles and as a result, the magnet deviates as it rolls. The deviation of the magnet from the weight force providing the magnet has been misaligned (due to an external magnetic force) can be modeled by the equation $F = mg\sin\theta\cos\alpha$ and used to estimate the final position of the magnet as it rolls down the plane.

3.2 How will varying the angle of incline affect the motion of the magnet?

3.2.1 Hypothesis

As the angle of incline is increased, the deviation will increase until a critical angle is reached.

3.2.2 Observations

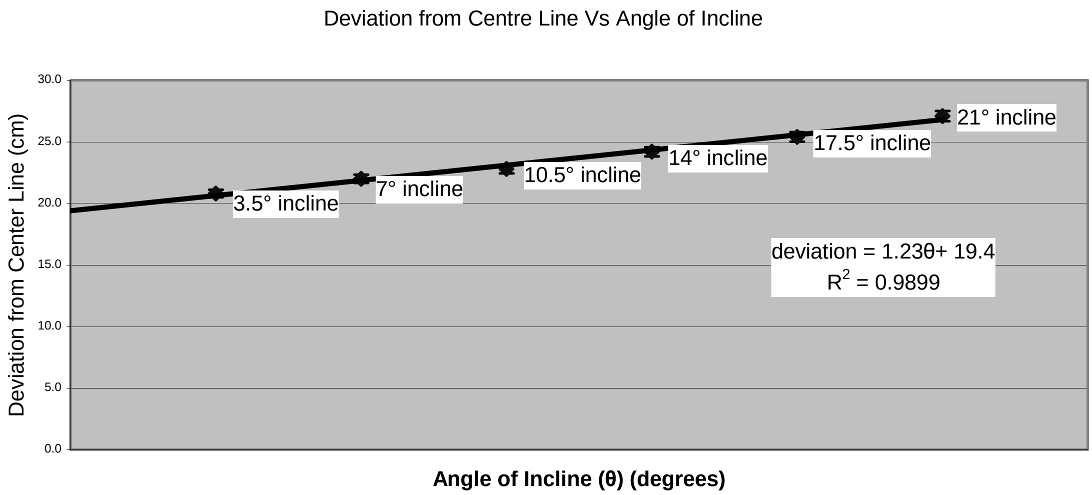
By raising the angle of the incline, the magnet was observed to have deviated more. However, if the ramp was raised past a critical angle (around 25 degrees), the magnet exhibited a sliding behavior instead of rolling behavior.

3.2.3 Results

Table 3 Deviation Results

	3.5° incline	7° incline	10.5° incline	14° incline	17.5° incline	21° incline
Average	20.8	22.0	22.8	24.2	25.4	27.1
Spread	0.8	0.9	0.5	0.7	0.9	0.5
Deviation	0.5	0.5	0.3	0.4	0.5	0.3

3.2.4 Analysis of Results



3.2.5 Discussion

The graph and its y-intercept value of 19.4 ± 0.3, indicate that, within experimental error, the deviation of a magnet from the centre line is directly proportional to the angle of the incline the ramp is placed at, provided the material and all other physical conditions remain constant. The slope of the graph of deviation from centre line versus angle of incline within the calculated experimental error of 0.02 equals 1.23 meaning that the deviation of the incline increases at the rate of 1.23cm/°. So, for every degree the incline is increased by, the deviation of the magnet from the centre line is increased by 1.23cm. The straight trendline and its R^2 value of 0.9899 indicates that the ratio of deviation to angle of incline is constant up to and including an angle of incline of 21°. The results therefore support the hypothesis saying that as the angle of incline is increased, the deviation will increase. However, using the graph, the relationship between the deviation and the angle of incline once the angle of incline is above 21° was not able to be modelled.

The sliding behavior exhibited by the magnet occurred because the resolved component of the weight force down the plane provides a greater acceleration negating the frictional force that turns it ie. $f > \mu_s mg\cos\theta$. Given that the sliding behavior was observed when the angle of inclination was greater than 25°, an approximation for the coefficient of static friction can be calculated. To do this, we assume that the force down the plane (F) is equal to the force of friction (*f*) and for the purpose of the following calculation, it is assumed that 25° is the angle at which the rolling cylinder began to slide.

$$F = f \leftrightarrow ma = \mu_S mg\cos\theta$$
$$a = \mu_S \times g \times \cos\theta \leftrightarrow g\sin\theta = \mu_S \times g \times \cos\theta$$
$$\sin\theta = \mu_S \times \cos\theta \leftrightarrow \mu_S = \frac{\sin\theta}{\cos\theta} = \tan\theta$$
$$\therefore \mu_S \approx \tan 25° \approx 0.467$$

Given the inaccuracy of this calculation, due to having to guess the critical angle, this calculation of the coefficient of static friction, μ_s, is further substantiated by Kurtus which states that the coefficient of static friction for metal on glass is 0.5-0.7 (9). If the magnet began to exhibit a sliding behaviour, the magnet would travel faster down the plane than a rolling magnet because all of a sliding magnet's potential energy is converted into linear kinetic energy whereas a rolling magnet's potential energy is converted into both linear and rotational kinetic energy.

Due to the fact that a camera was unable to be used in recording the deviation, there is more likely to be error associated with the measurement of the deviation. While every effort was taken to eliminate error, the experimentation was conducted inside a concrete physics laboratory building which increases the likelihood of errors in the measurements due to an interaction with other magnetic materials, such as a steel support beam. I was also unable to find a level, so the longitudinal level was unable to be verified. There were also some significant vibrations occurring in the classroom due to other people conducting experiments with low frequencies. These vibrations may have caused error in the deviations.

3.2.6 Conclusions

The results support the hypothesis in saying that within experimental error, a plot of deviation of magnet from the centreline versus angle of incline results in a linear relationship up until and including 21°.

3.3 How will varying the material of the incline affect the motion of the magnet?

3.3.1 Hypothesis

Using an aluminium incline, as opposed to a wood incline, although having less friction, will result in a slower time and a larger deviation of the magnet, due to eddy currents being created as the magnet moves and acting to oppose the motion of the magnet.

3.3.2 Observations

For the majority of trials, the magnet was observed to deviate more on the aluminium plane than on the wooden plane. The time taken for the magnet to roll down the aluminium plane was significantly greater than the time taken to roll down a wooden plane.

Results

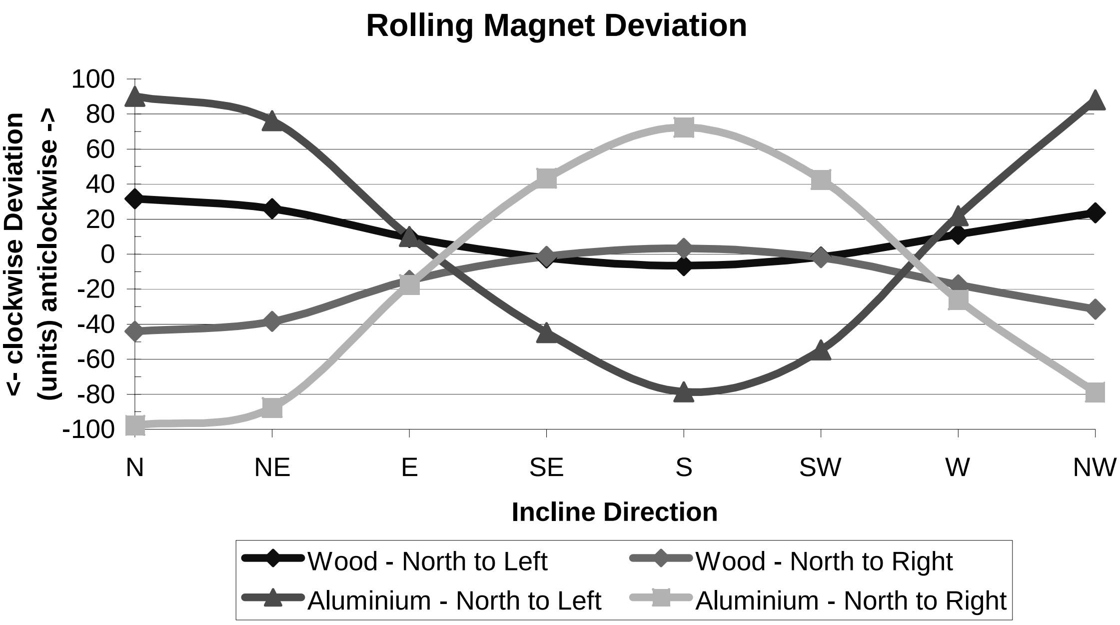
Deflection - Aluminium																
	N		NE		E		SE		S		SW		W		NW	
Mag N	E	W	SE	NW	S	N	SW	NE	W	E	NW	SE	N	S	NE	SW
Average	90.1	-97.8	76.2	-87.5	10.0	-17.3	-44.8	43.4	-78.7	72.4	-54.6	42.6	21.9	-26.1	88.1	-78.8
Spread	4.0	3.0	3.0	5.0	3.0	2.0	4.0	7.0	5.0	5.0	5.0	5.0	2.0	4.0	5.0	6.0
Deviation	2.1	1.8	1.8	3.5	2.0	1.3	1.8	3.6	2.7	2.6	2.6	2.6	1.1	2.1	2.9	3.8

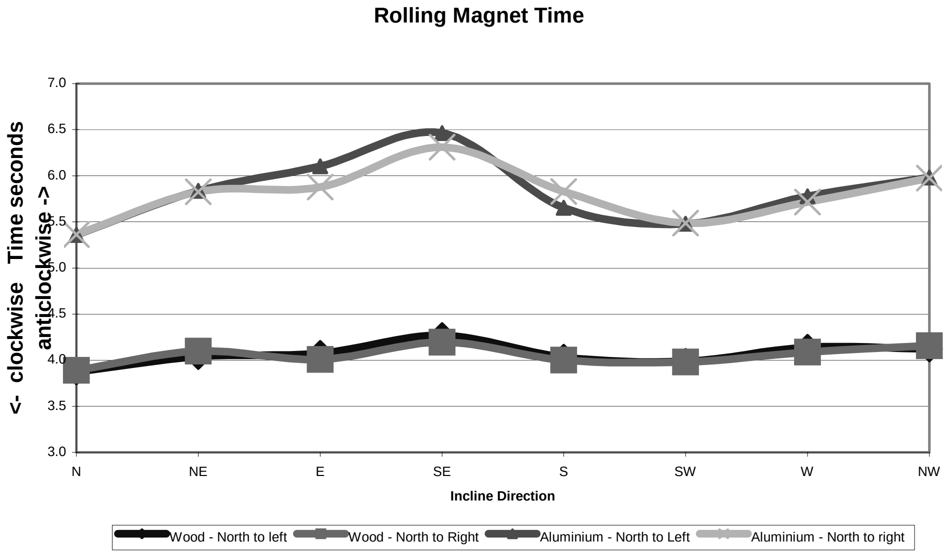
Table 4. Deviation on Aluminium Results

	N		NE		E		SE		S		SW		W		NW	
Mag N	E	W	SE	NW	S	N	SW	NE	W	E	NW	SE	N	S	NE	SW
Average	5.36	5.36	5.84	5.83	6.10	5.88	6.46	6.31	5.65	5.83	5.48	5.49	5.78	5.71	5.98	5.98
Spread	0.12	0.09	0.18	0.24	0.13	0.14	0.19	0.14	0.32	0.33	0.20	0.30	0.33	0.26	0.23	0.24
Deviation	0.07	0.06	0.07	0.15	0.08	0.07	0.13	0.08	0.19	0.18	0.12	0.15	0.17	0.19	0.12	0.14

Table 5. Time on Aluminium Results

Analysis of Results



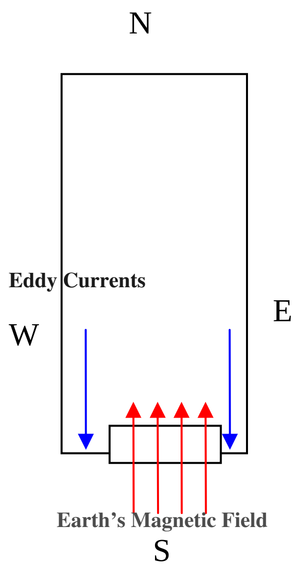


3.3.3 Discussion

The graph showing deviation of the magnet on material versus incline direction shows that the deviation of the magnet, when rolled down an aluminium ramp is much greater than on wood. All lines follow similar curved relationships as the incline direction changes.

The deviation of the magnet on both aluminium and wood is the same when the ramp rolled east. The minimum deviation for the magnet on aluminium occurs when it is travelling east and west (approximately). This is because as the magnet rolls down the plane towards the east (for example), the eddy currents produced are in a direction perpendicular to the earth's magnetic field. As a result, there is no parallel force vector which adds to changing the direction of motion.

When the magnet is rolling due north on aluminium, the eddy currents have to act against the Earth's magnetic field



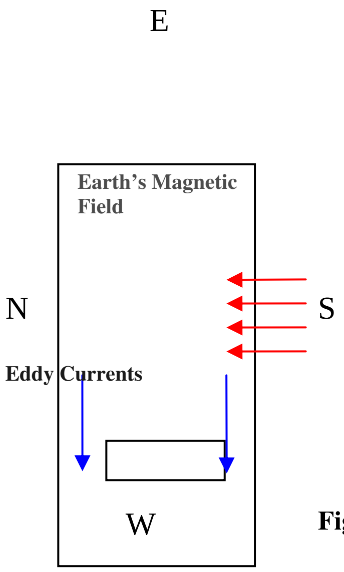


Figure 13. Rolling North on Aluminium

Figure 12. Rolling East on Aluminium

The time taken for the magnet to roll down the aluminium plane was significantly greater than the time taken to roll down a wooden plane which is attributed to eddy currents opposing the magnet's motion as it rolled down the plane.

In order to attempt to calculate the effects of the eddy currents produced in the aluminium, it was assumed that both the aluminium and wood had a similar static coefficient of friction, μ_s. In actual fact, the wood had a slightly larger μ_s. This was measured by rolling down a non-magnetic cylinder of similar size to the magnet down each plane and measuring the time taken for it to reach the end of the ramp.

<table>
<tr>
<td>
<u>Calculation of Current:</u>
$P = I^2R$ = J/s = 0.008J/5.81s = 0.00138J/s

I^2R = 0.00138J/s
I = $(0.00138/2.65\times10^{-5})^{0.5}$ = 7.2 amps

EMF=IR = 7.2 x 2.65×10^{-5} = 1.9×10^{-4}V

<u>Calculation of temperature increase:</u>
Shc = Energy x $mass^{-1}$ x $Temperature^{-1}$ = J x kg^{-1} x K^{-1}

Therefore,
T = Energy x $mass^{-1}$ x specific $heat^{-1}$ = J x kg^{-1} x $(J \times kg^{-1} \times K^{-1})^{-1}$ = K

T = 0.008J/3.24kg/900 = 2.74×10^{-6}K

There is no temperature increase which could be observed.
</td>
<td>
Energy lost by magnet:
On wood (E_w) = 0.002J
On aluminium (E_{al}) = 0.010J
$E_{al} - E_w$ = 0.008J

Area of eddies = 0.0025m^2
Av vel wood (v_w) = 0.48ms^{-1}
Av vel aluminium (v_{al}) = 0.33ms^{-1}

Resistance of Al = 2.65 x 10^{-5} Ω
Weight of whole Al = 3.24kg
Vol of Al = 0.0012m^3
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</table>

With a temperature increase of 2.74×10^{-6}K, even with the large number of trials completed, the temperature increase would be negligible because any increase would be lost to the surrounding environment. Using the previous calculation for current and as a result EMF, it is possible to measure the magnetic field created to oppose the motion of the magnet as it rolled down the aluminium plane.
Where F_E is the force of the electric field, F_B is the force of the magnetic field, q is the charge on an electron, E is the electric field strength, v is velocity, B is the magnetic field strength, V is the voltage, d is distance, EMF is the induced voltage and L is the length of the conductor. For the purpose of this calculation, the length of the conductor was taken to be the diameter of the eddy currents combined. Given that the magnetic field strength of the magnet was found to be 36mT, the value for the eddy current's magnetic field strength of 7.35mT is acceptable.

$$F_E = F_B \rightarrow qE = qvB$$

$$E = vB \rightarrow \frac{V}{d} = \frac{EMF}{L} = vB$$

$$\frac{1.9\times10^{-4}}{0.08} = 0.33B$$

$$B = 7.35mT$$

v = 0.33ms^{-1}
EMF = 1.9×10^{-4}V
L = 0.08m

The deviation of the magnet on aluminium when travelling south was 75% of the deviation value when the magnet was rolling north. However, the deviation of the magnet when rolling south on wood was a mere 25% of the deviation recorded when the magnet rolled north. This is most likely attributed to the eddy currents creating a significantly stronger force than the Earth's magnetic field, meaning that it has more influence over the motion of the magnet than

the Earth’s magnetic field does. On both the wood and aluminium ramps, the time taken for the magnet to roll down the plane was greatest when it rolled in a south east direction and shortest when it rolled north. Although it is very difficult to produce a justifiable explanation as to why this occurred, the most likely cause is due to the angle of inclination of the Earth's magnetic field.
Errors for this experiment could have occurred due to the aluminium becoming dirty and irregular. The error associated with this was minimised by wiping down the aluminium regularly with a damp cloth and leaving it to dry. The deviation scale was sticky taped onto the aluminium surface, so this could have interrupted the most of the magnet just before it crossed the deviation scale. This error was minimised by ensuring a single piece of sticky tape ran across the front edge of the scale and was pressed flat against the aluminium. A hand was placed on the ramp after each trial to ensure any residual currents in the aluminium were removed. The same precautions and error minimising steps were taken in this experiment as in experiment one.

3.3.4 Conclusion

The results support the hypothesis in saying that a magnet deviates to a greater extent on an aluminium plane than a wooden plane due to eddy currents created in the aluminium. These eddy currents oppose the motion of the magnet, causing it to roll down the ramp at a slower speed than on a wooden incline.

3.4 Investigation into motion near the edge (qualitative)

If the plane is aligned with the North-South field lines, the magnet still exhibits turning behaviour due to the eddy currents present in the aluminium. However, as the magnet approaches the edge of the aluminium, there are only eddy currents on one side of the magnet. This results in the magnet travelling back into the middle of the aluminium.

4 Conclusions

4.1 Conclusions for nonconductive planes

The magnet deviation depends on which way the poles are orientated due to interaction with the Earth’s magnetic field. The larger the angle of the plane, the higher the deviation of the magnet.

4.2 Conclusions for conductive planes

When a magnet rolls down an aluminium plane, eddy currents are created in the aluminium which oppose the magnet’s motion down the plane. When super magnets roll down an aluminium plane, the eddy currents are stronger which produces a stronger correcting force.

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6 Reference List

[1] Oxford English Dictionary [book on CD-ROM]. 3rd ed. New York (NY): Oxford University Press; 2002.

[2] Brito L, Fiolhais M, Paixao J. Cylinder on an incline as a fold catastrophe system. Eur J Phys 2003;24:115-23.

[3] Resnick R, Halliday, D. Physics Part 1. 3rd Ed. New York: John Wiley & Sons; 1977.

[4] Serway RA, Jewett JW. Physics for Scientists and Engineers. 6th ed. Belmont (CA): Thomson Learning; 2004.

[5] Walding R, Rapkins G, Rossiter G. New Century Senior Physics. South Melbourne, Australia: Oxford University Press; 1999.

[6] National Geophysical Data Centre (NGDC). Estimated Values of Magnetic Field Properties [Online]. 2004. [Cited 2006 May 18]; Available from: URL:http://www.ngdc.noaa.gov/seg/geomag/jsp/IGRFGrid.jsp

[7] Tom. Magnet's floating in the Earth's field [Online]. [2001?] [cited 2006 Apr 13]; Available from: URL:http://van.hep.uiuc.edu/van/qa/section/stuff_about_space/the_earth_and_the_moon.html

[8] Magnetic fields and how to make them [Online]. 1999 [cited 2006 Apr 13]; Available from: URL:http://physics.bu.edu/~duffy/PY106/MagField.html

[9] Ron K. Lab Mag Field Lines [Online]. 2001? [Cited 2006 Apr 13]; Available from: URL:http://www.emporia.edu/physics/keithron/collegelab2/magnetic_lines.htm