Experimental Physics I
(Course PHY 121)

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General Information

Experimental Physics is not meant to be a supplement to theory! It is a different way of understanding the Universe. It does offer the ultimate test of a theoretical model. This course is designed to teach you how to approach experiments and make sense of the results. You are not expected to follow the procedure mechanically – feel free to make changes to the procedure and analysis in consultation with the TA/Faculty to improve the experiment and to learn more out of it.

The Experiments

Experiments to be done as part of this lab are grouped as follows

A. Mechanics

    (a) Oscillations (Harmonic and anharmonic motion)

        i. Physical Pendulum

        ii. Coupled Pendulum

    (b) Elasticity of materials

        i. Torsional Pendulum

        ii. Young's Modulus

    (c) Retarded motion

        i. Viscosity

        ii. Euler's method to determine coefficient of friction

B. Electricity and Magnetism

    (a) Faraday's and Lenz's Law (interdependence of **E, B**)

    (b) Generating a uniform B field (Helmholtz coil)

    (c) Magnetic field and its spatial dependence (Repulsion between magnets)

    (d) Measurement of small currents/charges (Ballistic Galvanometer)

C. Optics

    (a) Refractive Index of a glass prism

    (b) Inverse Square law of Light Intensity

References

A generally useful book for this course is *Art of Experimental Physics* (by Daryl Preston), of which the library has several copies. In addition to this manual, there are manuals pertaining to some experiments. Do refer to them for details of the instrument and the procedure for making measurements.

About this manual

The descriptions of the procedures and the instruments appearing in this manual are only meant to give you an overview of the experiments to be done in this course. The manual provides neither a step-by-step description of the procedure, nor a full analysis of the experiment. You have to put in your effort to read up and understand the finer details.

    Please make sure that this printed copy stays with the apparatus. Do not take this away. You can get an electronic copy from the instructors.

Safety and Security in the Lab

Whenever you work in your lab, you should be aware of the possible dangers and hazards. This lab has relatively low level of dangers or hazards inherent to the apparatus. Nonetheless, there are dangers all around us, and we must be aware of them and try our best to prevent accidents.

- Accidents can be simple ones: such as cutting yourself by a blade or puncturing your muscle by a wire or a pin, or dropping something heavy on your foot. So, it is vital to pay attention to everything you do, no matter how small the task is.

- It is important to learn the correct use of all equipments, tools, and instruments. Incorrect use of even very ordinary instruments can lead to serious injury.

- Read carefully the manuals provided with the apparatus. This will prevent inadvertent damage to the instrument as well as improve the safety of the user.

- Electrical hazards (shock, short circuit) can spring quite easily if proper procedures are not followed. Use insulated tools where necessary. Switch off power when devices are not in use. Switch power on in the proper sequence. Be cautious about high currents or high voltages.

- Improper use or poor maintenance of electric outlets/equipment can lead to short circuit and fire. Be vigilant! Make sure you know where the mains switchboard or contact breakers are in the lab. *Turn them off in case of an accident,or if you suspect something is going wrong. But do this only if you can do this without taking undue risks, otherwise leave it alone.*

- Make sure you know where the fire extinguishers are located and read the instructions on them right away. Don't wait for a fire to start before you find out about them.

- Know where the escape routes are. In case there is an accident, fire, etc, leave the lab by the escape route *rapidly, but in an orderly manner, without rushing, without pushing each other, and without panic.*

Structure of a Lab Report

On the day of the experiment

- Date:

- Title:

- Tabulation of primary measurements

- Signature of the TA /Faculty
  Please ensure this – the onus of getting your procedure and results checked by a TA/Faculty is on you, not the TA/Faculty

Subsequently

- Goal/Importance of the experiment:
  Please do not repeat the lab manual – summarise in a few lines only

- List the essential equations to go from the measured quantities to the final result

- Propagation of error through the above equations

- Derived quantities (including the error), finally ending with the result
  the derived quantities must be neatly tabulated where possible

- Graphs
  see the notes for what makes a good graph

- Discussion: Compare the experimental result with theoretical prediction, and discuss experimental issues (shortcomings, problems, solutions if any).

Grading and Evaluation

You are expected to carry out at least 8 experiments, and at least one experiment from each group. Additional work, done properly, and novel initiatives will be rewarded.

- 50% towards continuous evaluation (during and after each experiment).

- 20% for Lab notebook with emphasis on real time data logging

- 30% for final exam/viva.

Lab Reports will have to be completed within a week of the experiment, in any case before the start of the next experiment. You will be assigned experiments according to a fixed schedule. Accordingly, you should prepare for the experiment ahead of time. Apart from the lab manual provided by us you should refer to other material elsewhere (library, internet, etc.)

Notes

1. Read the write-up on the experiment before you start on it. Since the lab is usually open have a look at the experimental set up as well.

2. Identify the derived and measured (independent) parameters.

3. Employ the largest possible range of the independent parameter in your experiment.

4. Have an idea of how errors propagate from the measured parameter to the derived parameter — the higher the power index in the relationship between the two, the faster the errors magnify while going from one to the other.

5. Always make more than one measurement of a parameter — typically 5–7 is a good number. Multiple measurements give you a more accurate representative value as well as an estimate of its accuracy.

6. Graphs are meant to be visual aids to analysis — make sure that they do aid! They should be neat, with the axes well labelled and marked with fiducial numbers. Make full use of the graph space — do not confine the plot to a tiny portion of the graph.

7. A computer printout of the graph is preferred though not mandatory.

8. If more than one measurement has been made at a value either show all the points on the graph or plot the mean and the standard error ... or plot both if they do not clutter the graph too much. Error bars should be shown even on individual points if they are available.

9. Plot the expected theoretical curve for reference on the same graph where appropriate and possible.

10. In general when two plots on different graphs are to be compared make sure that both are plotted to the same scale, and if practical, the same range.

11. Put some thought into plotting the right quantities in a graph — they need not be either the measured or the derived quantities. The plotted variables may be some modified version of the two. Ease of subsequent analysis and conveying the meaning should be the guiding principle behind each graph.

12. Where one needs to estimate parameters from the graph plot transformed versions of the measured and derived quantities such the plot is a straight line and the required estimate is either the slope of the line or one of the intercepts.

13. Overplot a smooth curve on the points scatter — Do not join the dots! This smooth curve should be based on physics (the theoretical reference curve) and not driven by a spreadsheet's choice of parameters.

14. Every measurement or estimate will have an associated error. It is absolutely essential to quote the same. Note that the error may not be the same as the discrepancy between the estimate of a parameter and its true value
Error: uncertainty in the measurement or estimate of a parameter
Discrepancy: Difference between the measurement/estimate and the true value
If we measure g = 8.9 $\pm$0.2 $\mathrm{m\,s^{-2}}$, the uncertainty or error is 0.2 whereas the discrepancy is 9.8 − 8.9 = 0.9 $\mathrm{m\,s^{-2}}$. A discrepancy much larger than the measurement error suggests systematic errors (also called bias) in the experiment.

It should be noted that the term *Error* is loosely used to mean either measurement/estimation error or discrepancy (as defined above). In this course students should be careful in their usage and must abide by the above.

Statistical Analysis

Multiple measurements of a physical quantity rarely result in a single value ... because of 2 reasons:

1. The quantity itself may be multi-valued ... heights of Indians

2. No measurement process has infinite accuracy ... temperature fluctuations, human error, errors in fiducial markings, instrumental malfunction, etc.

   There are two kinds of measurement errors:

   - systematic errors (bias): this results in the measured value always being offset by a fixed amount from the true value ... e.g. a weighing machine with a spring which has undergone plastic deformation, or a scale in which each "millimeter" interval is only 0.99 millimetre

   - random errors: this results in a scatter of measured values on either side of the true value. In general, both kinds of errors will occur in an experiment though one or the other may dominate. Furthermore, the magnitude of the two errors can vary in different regions of the parameter space ... e.g. a deformed spring will result in different systematic errors for objects of different masses.

Therefore, in the real world one is forced to deal with a distribution of values and in an experiment we have to make multiple measurements ... the more the better. Consequently, from these multiple measurements one has to extract a representative value and a dispersion. Statistics is a technique for determining the number of measurements to make, extract representative single values from a distribution, and estimate the accuracy of the representative value. Furthermore, since resources are finite and one cannot measure every single value of a distribution (think of the heights of Indians), statistics is also used to translate the representative value from a (sub-) sample to the true value for the whole population. In general, the sample value will be different from the true population value. Statistics tells us how to design our experiment to make this difference as little as is required to reach some conclusion ... e.g. Are Indians taller than the French ?

   We will discuss 3 different groups of statistical parameters here:

1. Representative values: mean, median, mode

2. Dispersion: variance and standard deviation (aka root mean square deviation — rms)

3. Standard error: error on the representative value

Mean (aka average or arithmetic mean) is the most common representative parameter used for a distribution. The mean for a variable **X**, observed through **n** measurements x_i, is denoted $\langle X \rangle$ or $\bar{X}$

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

where, w_i is the weight of each x_i. If the weights are all equal then we obtain the more commonly used expression

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Median is the central value (or the average of two central values) when the measurements are all arranged in an ascending (or descending) sequence.
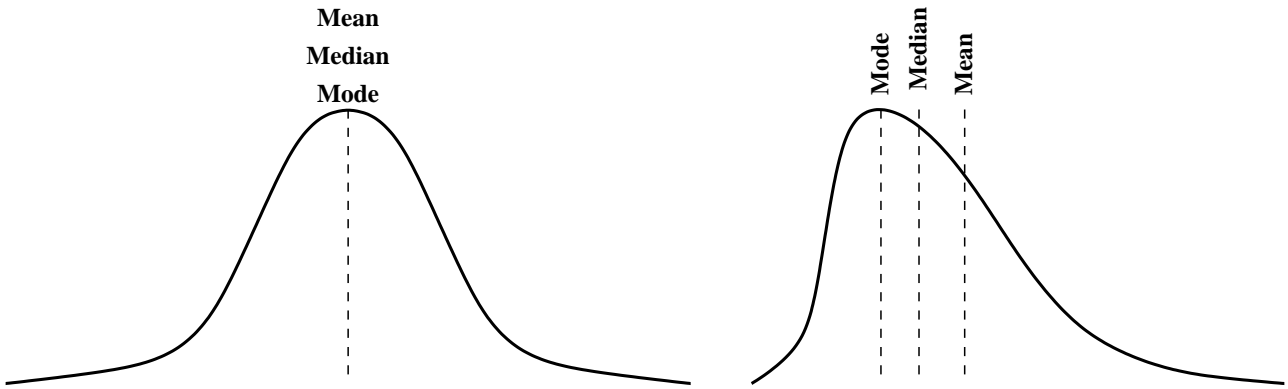
Figure 1: The behaviour of mean, median and mode for symmetric and asymmetric distributions. The asymmetry may either be intrinsic to the parameter, or it can be due to a large number of spurious (error) values. The mean is best for a smooth and well-behaved distribution, but it can be significantly affected by large outliers.

Mode   is the value with the highest frequency of occurrence.
No one parameter is better than the others in all situations:

- Mean: is the most representative central value for a good distribution.

- Median: is a more stable central value in the presence of outliers or when the number of measurements (n) is small.

- Mode: is always guaranteed to be identical to one of the measurements, whereas neither the mean nor the median may be equal to one of the measurements. But, the mode can be at an extreme of the distribution.

Standard Deviation

The standard deviation, or the root mean square (RMS) deviation of the parameter **X** is given by

$$\sigma_x = \sqrt{\frac{\Sigma_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{n}{n-1}\left(\overline{x^2} - \bar{x}^2\right)} = \sqrt{V_x}$$

where, V_x is the variance of the distribution. Note that the denominator is $n-1$ and not n.

A narrower distribution will have a smaller standard distribution. Further, in the case of a standard curve the probability of occurrence of a value is defined given the mean and the standard deviation (see Fig. 2) In the presence of noise approximately 68% will lie within 1σ of the mean, 95% within 2σ and 99.74% within $3\,\sigma$. The probability that a measurement falls outside 3σ due to statistical fluctuations due to error is only 0.26%. Therefore, any measurement value deviating from the expected (or mean) value by more than 3σ is unlikely to be due to measurement error and hence suggests that the model from which the expected value was derived was incorrect.

Standard Error: the error on the mean

It should be obvious that randomly selected sub-samples from a population will in general have means which differ from each other. In general, this difference is related to the standard deviation of the parent sample and the number of measurements in the sub-sample Usually, the mean values of the various sub-samples themselves form a distribution whose standard deviation is equal to the standard deviation of the parent population divided by the square-root of the number of measurements in each subsample. Therefore the error on the mean value is given by

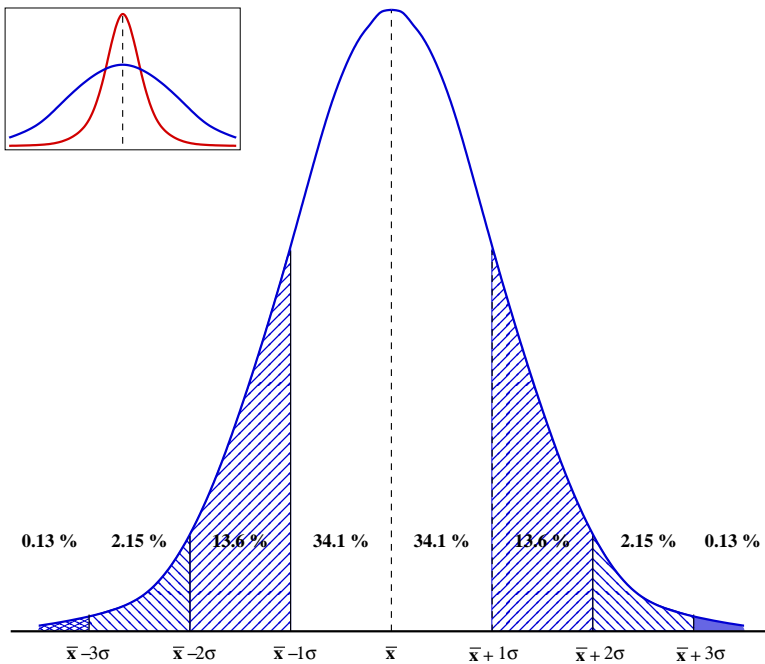$$\sigma_{\overline{x}} = \frac{\sigma}{\sqrt{n}}$$

Figure 2: Gaussian or Normal distribution. Inset: A narrower distribution will have a smaller distribution than a broader one. The main figure shows the integral probability of the distribution within the corresponding region.

A measured value has no meaning unless it is accompanied by its error. In text a measurement is usually written as [mean $\pm$ std.error]. Sometimes the error quoted is thrice the above value (for a 3σ range).

On a graph the mean values are plotted as points while the error on each are plotted as a vertical bar, whose length indicates either the standard error or three times its value (see Fig. 3). When a theoretical model differs from a measured value by much more than its error bar it means either that the data is wildly wrong, or more usually that the theoretical model on which the prediction is based is inappropriate. In Fig. 3, the straight-line fit dos not fit all the data and therefore only has a limited range of validity. On the other hand the non-linear (dashed) curve fits the data over the entire range. Usually, deviations from a simple model occur at one or the other extreme of the range of independent parameter values. Therefore, it is important to explore as large a range of the parameter space as possible.

The error on the particular value of a variable may be determined either by making multiple measurements and determining the standard error or by an estimate of various errors in the experimental set up. If the error model is correct the measured error should match the estimated error. Alternatively, one can make measurements of a known phenomenon and estimate the error from the scatter around the model curve (Fig. 4).
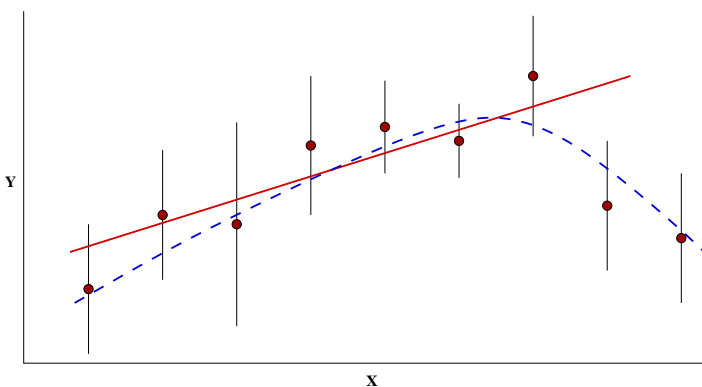

Figure 3: Error bars on data. The error bars indicate the range within which the *true* value is likely to be given the measured value. Any theoretical model seeking to explain measurements must fall within the error bars. In this figure the straight line fit (solid line) is only valid range of the data, while the non-linear curve (dashed line) fits all the points.

Error Propagation

In general the quantity that we wish to estimate is usually not directly measured but estimated from measurements of other parameters; e.g. we measure velocity by measuring the distance travelled
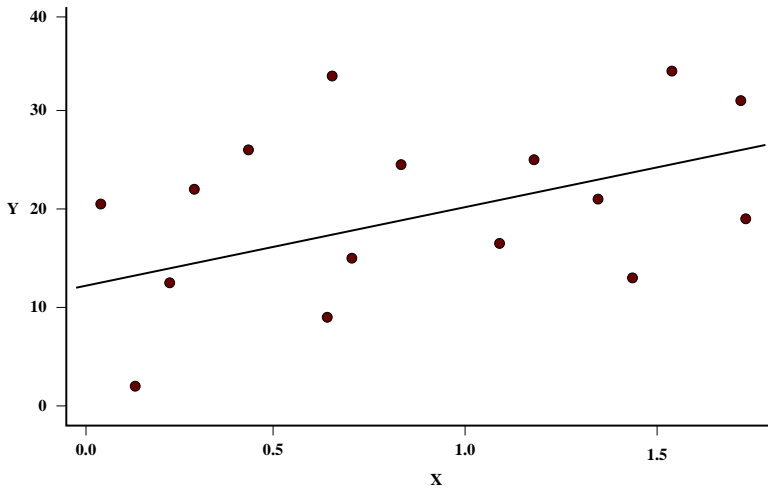
Figure 4: A known model (solid line) along with measured values. Under the assumption that the errors are the same for all measurements one can estimate the error by measuring the deviation of the points from the model curve.

in some time interval. Therefore, any errors in the measurement of both distance and time will contribute to the error in the velocity estimate. This cascading of errors is termed error propagation. If the desired secondary quantity (X) is a function of one or more primary (or secondary) quantities A, B, C

$$X = f(A, B, C, \ldots)$$

then

$$\Delta X^2 = \left(\frac{\delta f}{\delta A}\right)^2 (\Delta A)^2 + \left(\frac{\delta f}{\delta B}\right)^2 (\Delta B)^2 + \left(\frac{\delta f}{\delta C}\right)^2 (\Delta C)^2 + \ldots$$

where, ΔX is the error on the mean value of X, and so on. Since the standard error on X is a measure of the error in the mean value

$$\sigma_X^2 = \left(\frac{\delta f}{\delta A}\sigma_A\right)^2 + \left(\frac{\delta f}{\delta B}\sigma_B\right)^2 + \left(\frac{\delta f}{\delta C}\sigma_C\right)^2 + \ldots$$

This expression is true only if the errors in A, B C, ... are not correlated with each other. Correlated errors are beyond the scope of this course and their analysis will not be taken up here.

Accuracy and Precision

Accuracy and precision are two words you will often encounter in the context of any measurement. Accuracy describes how close the measured value of a parameter is to the standard or true value. *An accurate measurement, or an accurate device gives values close to true value.*

If a measurement is repeated several times, we expect the values to cluster around a certain value. Precision is a measure of how close to each other several measurements are; it is an indicator of the scatter in the data. High precision implies small spread or scatter of values.

The graph (Fig. 5) explains the difference between accuracy and precision very nicely.
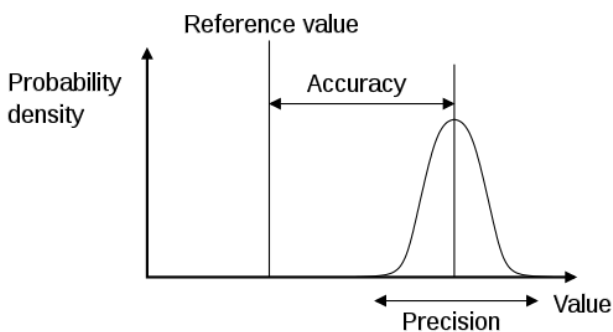

Figure 5: A measurement will result in a scatter of values. The extent of scatter represents the precision of the measurement, while the deviation of the mean of the measured values from the true, or reference, value represents its accuracy (Figure courtesy: Wikepedia)

9

Physical Pendulum

Motivation and Aim

A real pendulum differs from the idealised simple pendulum usually analysed in text books in several ways. For one, the mass is not all concentrated at a single point. Therefore, both the kinetic energy and the effective length of the pendulum depend on the distribution of mass, which in turn affect the dynamics of oscillation. Further, if the pendulum is not in vacuum air resistance will cause a progressive reduction in the amplitude of oscillation. Finally, the expression for time period usually seen in text books is an approximation valid only for small angles. Here we determine the period of oscillation of a physical pendulum, which is a massive bar on which supplementary mass can be attached at any point.

Apparatus

1. Rod and cylinder assembly
2. Pasco apparatus with photogate
3. Measuring scale
4. Vernier callipers

Procedure

Determine the moment of inertia and the centre of mass of the pendulum. Set the pendulum into oscillation and gain familiarity with measuring the period using the photo gate.

1. Do not detach the bar from the pivot to measure or weigh it. The length of the bar from the pivot to the end is 355 mm, its diameter is 8.9 mm and its mass is 26.9 g.

2. Measure the period for a small angle of oscillation (how small?) - T_0. How does this compare with the theoretical expression?

3. Repeat the above measurement for progressively larger amplitudes of oscillation — $T(\theta_0)$

4. Allow the pendulum to oscillate 20–30 times and measure the change in period. Do this for one small amplitude and one large amplitude.

Theory

The motion of a physical pendulum is governed by the equation

$$I\frac{d^2\theta_0}{dt^2} + mgL\sin(\theta_0) = 0$$

where, I is the moment of inertia of the pendulum *about the pivot point*, L is the distance of the centre of mass from the pivot point, m is the mass of the pendulum and g is the acceleration due to gravity. The time period for small angle approximation is

$$T_0 = 2\pi\sqrt{\frac{I}{mgL}}$$

The time period for larger angles is given by

$$T(\theta_0) = T_0\left(1 + \frac{1}{4}\sin^2\frac{\theta_0}{2} + \cdots\right)$$

Analysis

1. Plot the period as a function of time over 20-30 oscillations. Does it change? if so, why?

2. Determine the relevant moments of inertia of the pendulum

3. Compare the experimental value of T_0 with the value obtained from I and L

4. Plot $T(\theta_0)$ and compare it to the expected functional form.

5. Determine T_0 from the plot in 2 different ways.

6. Determine T_0 by averaging the values for different values of θ_0.

7. Explain in your report how you minimise the error on the measurement of θ_0.

Points to Ponder

1. How does the photogate work?

2. Will you determine the period from a single oscillation or by averaging the time interval for multiple (how many?) oscillations?

3. How would you locate the centre of mass of the pendulum by a direct measurement?

4. What is your error estimate for the centre of mass determined geometrically?

Coupled Pendulum

Motivation and Aim

Every oscillator has a natural frequency. In the case of a mass attached to a spring the natural frequency is governed by the spring constant and the mass, and for or a pendulum, by the length of the pendulum and the gravitational acceleration. If two oscillators are coupled, and one oscillator is set in motion, the second is driven by the first.

Apparatus

1. Couple pendulum assembly
2. Stopwatch
3. Measuring scale
4.

Procedure

Theory

Let $\theta_{1,2}$ be the (small) angular displacements of the two pendulums (we can then write $\sin\theta \approx \theta$). The pendulums are assumed to be simple harmonic, of length l with a bob of mass m. The coupling between the pendulums is assumed to be weak, i.e. the restoring force for an isolated pendulum is much greater than the force due to the coupling. The coupling force is taken to be of the form $f = -k(\theta_a - \theta_b)$, the equation of motion for the coupled system is

$$
\frac{d^2\theta_a}{dt^2} + \frac{g}{l}\theta_a + \frac{k}{ml}(\theta_a - \theta_b) = 0, \quad \text{and}
$$
$$
\frac{d^2\theta_b}{dt^2} + \frac{g}{l}\theta_b + \frac{k}{ml}(\theta_b - \theta_a) = 0.
$$

We assume harmonic solutions of the form $\theta_{a(,b)} = \theta^0_{a(,b)}\sin(\omega t + \phi)$, which upon substitution above yields two values of ω

$$
\omega_1^2 = \frac{g}{l}, \quad \omega_2^2 = \frac{g}{l} + \frac{2k}{ml}
$$

For the first mode the pendulums are in phase, in the second mode they are out of phase. The amplitudes are identical in both cases.

Analysis

Determine the phases of the two pendulums. What happens if the two pendulums are not identical? This can be tested by changing the length of one of the pendulums.

Points to ponder

1. What happens if the coupling is very weak? Very strong?

2.

3.

Further Reading

1. Article by Vittorio Picciarelli and Rosa Stella (PHYSICS EDUCATION v45 i4 p402 (2010))

Torsional Pendulum

Motivation and Aim

All materials exhibit elasticity, i.e. there is a restoring force to retain the shape against an distorting external force. The external force may cause an elongation, compression, shear etc. When a wire is twisted, a restoring torque is produced, which is related to the torsion constant and the modulus of rigidity. This results in oscillations whose period can be measured to determine the required quantities. In this experiment we determine the torsion constant and modulus of rigidity of a steel wire.

Apparatus

1. Aluminium frame with 2 G-clamps
2. A split rod with 2 rings
3. Allen screws (x2) and wrench
4. Steel wire
5. Vernier callipers
6. Screw gauge
7. Stop watch
8. S-shaped hook
9. Heavy mass

Procedure

The experimental setup is shown in Fig. 6. Stretch the steel wire along the centre of the frame and assemble the torsional pendulum to swing freely about the wire and in a plane perpendicular to it. Make sure the rings are symmetrically placed with respect to the wire and the split rods.

1. Measure the dimensions of the components of the pendulum and determine its moment of inertia.

2. Clamp the split rod at a distance $D_1 = 10$ cm from the top. Measure the time interval for 10–30 oscillations and determine the period of one oscillation T. Why should we determine the period from multiple oscillations? What should determine whether you should use 10 oscillations or 30 or something in between?

3. Repeat the procedure for different values of D_1.

Theory

The motion of a torsional pendulum is governed by the equation $I\ddot{\theta} + c\theta = 0$, where, I is the moment of inertia of the oscillator and c is the torque per unit twist. The measured and derived quantities are related through the following equations. The symbols related to measurable quantities are depicted in Fig. 7.

Oscillation Time period $\quad T = 2\pi\sqrt{\dfrac{I}{c}}$

Moment of Inertia $\quad I = \dfrac{M_{rod}}{12}\left(L^2 + B^2\right) + 2M_{ring}\left[\dfrac{h^2}{12} + \dfrac{R_1^2 + R_2^2}{4} + r^2\right]$

Torque per unit twist $\quad c = \alpha\left(\dfrac{1}{D_1} + \dfrac{1}{D_2}\right)$

Torsion constant $\quad \alpha = \dfrac{\pi a^4 \eta}{2} \qquad$ a: radius of the wire; η: modulus of rigidity
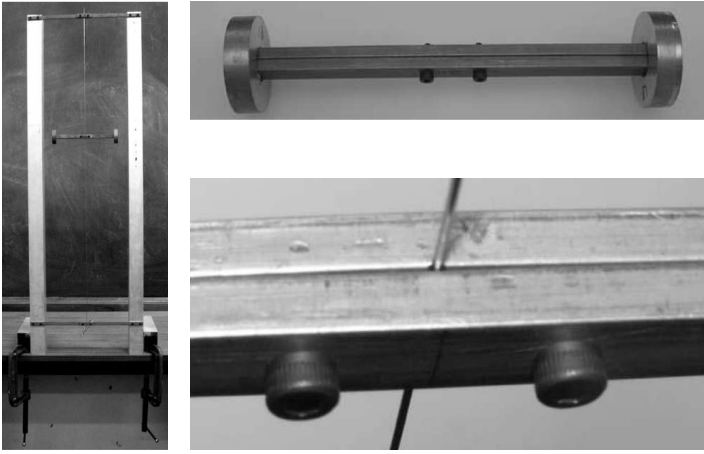
Figure 6: *Left:* The entire experimental setup. *Top right* The torsion pendulum consisting of split rods, rings and allen screws. *Bottom right:* A close-up of the pendulum pivoted around the wire.
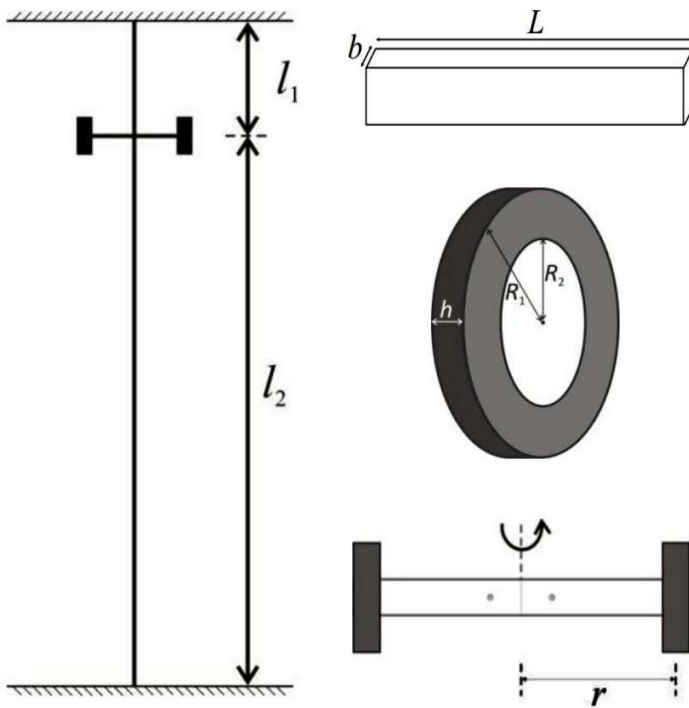

Figure 7: *Left:* The distances — D_1 and D_2 — of the pendulum from the edges of the frame. *Top right:* The length (L) and breadth (B) of the split rods (taken together) in the plane of oscillation. *Mid right:* The inner and outer radii, and thickness of the rings. *Bottom right:* The radius of the pendulum

Analysis

1. Determine the torque per unit twist (c) for different values of D_1 and plot the same.
2. Determine the torsion constant from the plot and also by averaging the values for different D_1.
3. Determine the modulus of rigidity.

Points to Ponder

1. What will happen if the wire has kinks in it ?
2. What will happen if the wire is not taut ?
3. How can the expression for moment of inertia be derived ?
4. What happens if the pendulum has additional motion parallel to the wire ?

Further Reading

Elements of Properties of Matter by D S Mathur.

Young's Modulus

Motivation and Aim

Materials exhibit a restoring tendency against tension (force along an axis) . A measure of the tensile elasticity is the the Young's modulus. It is defined as the stress (force per unit area) along an axis over the strain (ratio of deformation over initial length) along that axis. In this experiment the application of a transverse stress on horizontal bars will cause them to sag and the deflection from the horizontal will be a measure of the strain induced.

Apparatus

1. Stand
2. Spherometer
3. LED

3. Weight holder
4. Set of 500g weights
4. Aluminium, bronze and steel bars.

Procedure

Fix a bar to the stand in a horizontal position and secured by screws both end. Attach the weight holder to the centre of the bar. Set up the spherometer and LED so that the latter glows when the spindle of the spherometer just touches the bar. Take a spherometer reading with zero weight and measure the deflection for every additional 500g (maximum 1.5 kg for aluminium and bronze, 3 kg for iron). After reaching the maximum measure the deflection while the weights are being removed as well. Repeat the experiment several times for each rod.

Theory

The Young's modulus for transverse deflection is given by

$$Y = \frac{MgL^3}{4BW^3\delta}$$

where, L is the length of the bar, B is the breadth, W is the width (along the direction of deflection), M is the mass added to the bar, g is the acceleration due to gravity and δ is the deflection of the rod from the horizontal

Analysis

1. Plot deflection *vs.* hanging weight — one graph per bar showing all the measurements.

2. On the same graph plot mean deflection (with error-bars) *vs.* hanging weight for all bars on a single graph.

3. Calculate the Young's modulus from the plot, and from the average of the values derived for each deflection measurement.

4. Compare the values obtained from known values for the respective bars.

5. In your report,

    (a) describe the possible sources of errors and the steps taken to minimise them
    (b) compare the results for the three materials

Points to Ponder

1. Derive the expression for Young's modulus.

2. Why is there a maximum limit for hanging weights? Why is it higher for steel?

3. How does the weight of the bar itself affect the experiment?

4. Does the rod deviate from the horizontal for zero hanging weight? If so, what may be the shape of the curve?

Further Reading

Elements of Properties of Matter by D S Mathur.

Coefficient of Friction – Euler's Relation

Motivation and Aim

Friction is present between all surfaces in contact. Friction is a retarding force, and prevents uniform motion of an object on a surface. Here we determine the coefficient of friction between a flexible cord slipping over a steel rod. Consider two unequal masses suspended at the ends of cord around a cylinder. The weight of the larger mass can be balanced by the lesser mass because of the role played by friction between the cord and the cylinder. The magnitude of friction will be proportional to the length of contact between the cord and the cylinder.

Apparatus

1. Retort stands (x2)
2. Cylindrical steel rods (x2)
3. Hanger with slotted weights
4. Pan with weights

Procedure

The experimental setup is shown in Fig. 8. Fix the stands and the cylindrical rods to form a parallel pair of horizontal bars at the same heights on a level table. Drape the cord over the two bars and connect the weight hanger with a fixed weight ($T_1 = Mg$) to one end and the empty pan to the other.

1. Drape the cord over the bars without completing a turn (Fig. 8a) and place identical masses in both pans. The masses should be adequate to keep the cord under tension.

2. Alternatively, keep the weight in one pan fixed $T_1(= m_1 g)$ and increase the weight $T_2(= m_2 g)$ in the other pan gradually, until the cord just slips.

3. Repeat the experiment for different values of T_1 (Try 5, 10, 15, 20 g). To have a good control on the driving weight, you may add steel balls one at a time to the pan.

4. Keep the value of T_1 fixed but vary the number of turns of the string around the bar (Fig. 8b: 0.25, 1.25, 2.25, . . . turns) and determine the value of T_2 as before.

5. Experiment with different types of cords, and with different types of contact (line contact, areal contact)

Theory

At the moment just before the cord starts to slip the forces are in equilibrium:

$$T_1 = T_2 \, e^{\mu \theta}$$

where, μ is coefficient of friction and θ is the extent of contact between the string and the cylinder expressed in radian. In the first case we keep θ fixed and vary T_2 to balance T_1, while in the second case we keep T_1 fixed and vary T_2 to offset the change in θ.

Analysis

1. Plot T_1 *versus* T_2 in the first case and T_2 *versus* θ in the second case.

2. Determine μ from the plots and also by averaging the values obtained from all the different measurements using the equation.
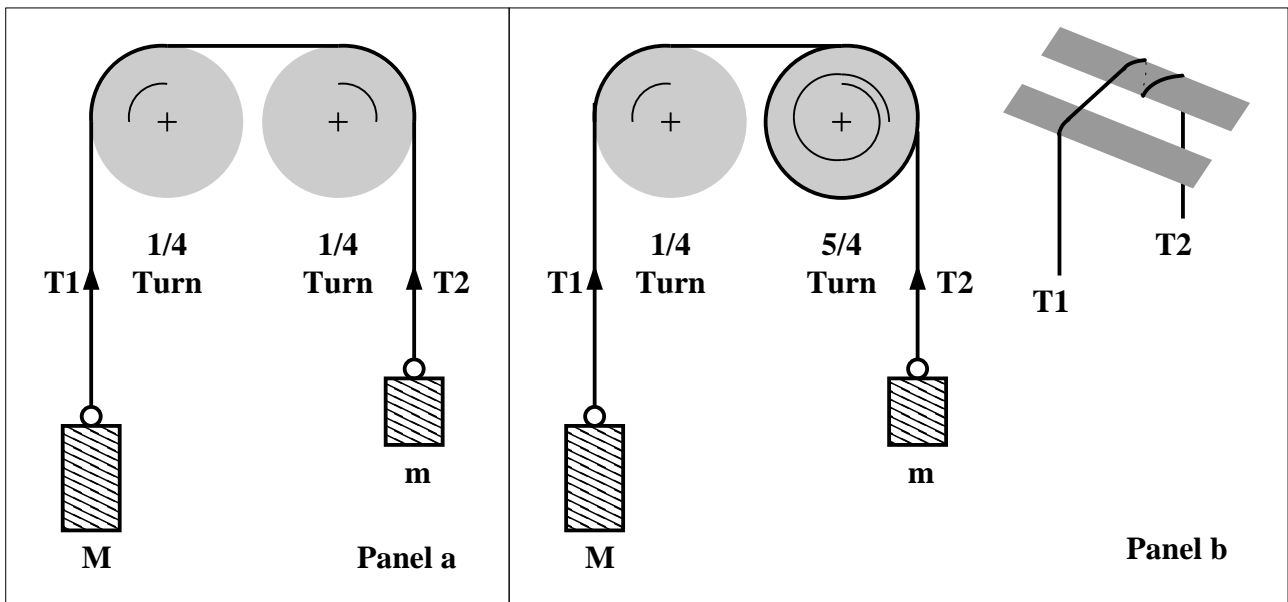
Figure 8: The experimental setup showing the cord draped around the two parallel cylindrical rods (shown in cross section). The two weights are attached to the two ends of the cord. The arcs shown inside the cylinders indicate the extent of contact between the cord and the cylinders. *Panel a:* Experimental set-up case 1, where the string is draped over the rods without a completing a turn and a relationship is derived between T_1 and T_2. *Panel b:* Experimental set-up case 2, where T_1 is kept fixed and the number of turns of the string is varied and the corresponding T_2 measured.

Points to Ponder

1. Instead of increasing the mass to make the string slip, can one derive μ by removing mass? If so, how?

2. Does this method measure static friction or kinetic friction?

3. What do you expect to happen if you were asked to make 100 measurements to achieve a very accurate value of μ for the same length of thread.

Viscosity

Motivation and Aim

Any fluid exerts a drag, called viscous force, on an object moving through it (i.e. in the presence of relative velocity). This property of the fluid is called viscosity. When an objects falls through a fluid under gravity its velocity, and hence the viscous drag force on it, increase until a limiting velocity is reached. At this *terminal velocity* the viscous force cancels the force due to gravity, and therefore the terminal velocity can be used to measure the viscosity of a fluid, which is the aim of this experiment.

Apparatus

1. Column filled with viscous fluid
2. Vernier callipers
3. Teflon and Steel balls of different diameters
4. Weighing balance
5. Stop watch

Procedure

Measure the mass and radius of the balls. Ensure that the liquid column is vertical. Gently drop the balls, one at a time, into the column and time their passage across the equidistant marks on the outer surface of the column. There are 4 such marks and the time taken to cross each segment should be used to confirm that the balls have reached terminal velocity.

Theory

The viscous force acting on an object is given by $F_V = 6\pi\eta a V_T$ where, η is the coefficient of viscosity, a is the radius of the sphere and V is the relative velocity. There is also the force of buoyancy which is equal to the acceleration due to gravity times the mass of fluid displaced by the object. When the forces of viscosity and buoyancy completely counteract the force due to gravity the object achieves terminal velocity. From these equations the coefficient of viscosity is given by:

$$\eta = \frac{2a^2 \left(\rho_{sphere} - \rho_{fluid}\right) g}{9V_T}$$

Analysis

1. Plot the terminal velocity *versus* $a^2 \left(\rho_{sphere} - \rho_{fluid}\right)$

2. Obtain the value of the coefficient of viscosity from the plot as well as by averaging the values obtained from individual measurements through the above equation.

3. Discuss in your lab report the issues associated with the velocity measurement and your efforts to minimise the errors.

Points to Ponder

1. Is it reasonable to expect that the viscous force of the liquid is independent of the material of the ball (steel and teflon)?

2. What will happen to your estimate of viscosity if the ball is hollow?

3. How will your result be modified, if at all, if the balls are thrown down with some velocity instead of gently dropped into the column (with zero initial velocity)

Faraday's & Lenz's Laws of Electromagnetic Induction

Motivation and Aim

Electric fields and magnetic fields are related to each other in a time dependent manner. These relationships are formulated as two laws: Faraday's and Lenz's laws of electromagnetic induction. To produce a time dependent magnetic field we simply let a permanent magnet perform harmonic motion, and we pick up the resultant electric signal by means of a a coil.

1. A magnet mounted on a pendulum and oscillates through an induction coil and the resultant EMF is measured by an external circuit. Increasing the amplitude increases the velocity of traverse of the magnet through the coil thereby increasing the rate of change of magnetic flux through the coil. Faraday's law is verified by demonstrating a linear relationship between the rate of change of flux and the induced EMF.

2. According to Lenz's law the induced current is in such a direction that the (secondary) magnetic field it produces opposes the rate of change of flux responsible for the induced EMF. Varying the resistance in the circuit will change the amount of induced current and hence the magnitude of the secondary magnetic field. As this secondary magnetic field dampens the motion of the oscillating magnet one can control the damping behaviour by varying the resistance ... thus demonstrating Lenz's law.

Apparatus

1. Semi-circular pendulum with bar magnet
2. Induction coil
3. Voltmeter
4. Shorting wire
5. Diode
6. Resistors
7. Capacitors

Procedure

Align the pendulum such that the magnet oscillates parallel to the (inductor) coil axis and symmetrically with respect to it. Time the period of oscillation; this period may be varied by changing the configuration of masses on the pendulum.

Faraday's law: Connect the circuit as shown in Fig. 9. The movement of the pendulum induces an EMF in the coil which charges the capacitor. The same will be measured by the voltmeter in the circuit. Record the induced voltage for different values of amplitude of oscillation (θ_0).
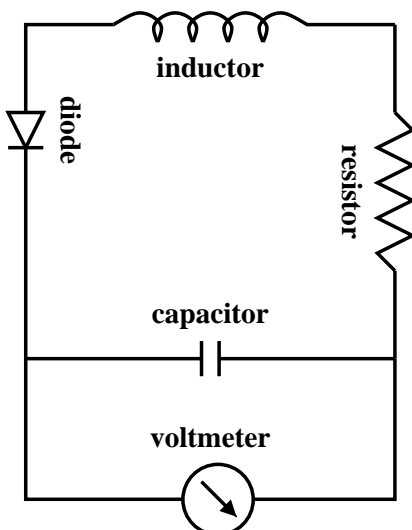

Figure 9: The circuit for charging the capacitor with the induced EMF. Choose an appropriate value of resistance and capacitance to get a voltmeter reading of 1–2 V for the largest amplitude.

Note

1. it will take several oscillations to build up the voltage across the capacitor. You may either measure the saturation voltage the capacitor or the voltage after a fixed number of oscillations.

2. Short the capacitor before the start of each experiment to discharge it completely.

3. Take at least 7 measurements for each value of θ_0

Lenz's Law   Disconnect the voltmeter from the previous circuit. Starting with a suitably large amplitude allow the oscillator to swing a large number of times. Measure the change of amplitude with successive oscillations. Plot amplitude as a function of oscillation number for (a) Resistance = ∞ (b) Resistance = zero and (c) Resistance = 2-5 Kilo ohm (how would you decide the value). Repeat the experiment at least 5 times for each of the above 3 resistance values.

Analysis

1. Faraday's Law: Plot the amplitude θ_0 *versus* induced EMF and discuss the same.

2. Lenz's law: Plot the amplitue θ_0 *versus* oscillation number for the 3 resistance values.

3. Discuss the following in your lab report:

   (a) The relationship between the rate of change of magnetic flux and the amplitude of oscillation?

   (b) The use of a diode in the circuit? Hint: see Figure 10

   (c) Explain why Lenz's law results in damping of the pendulum.

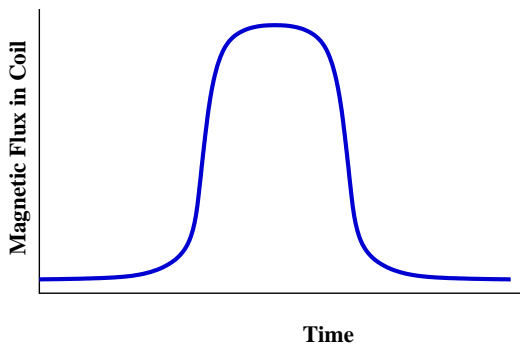   (d) How do you minimise the error on the measurement of θ_0?

Figure 10: A plot of the magnetic flux in the coil as a function of time

Points to Ponder

1. Why does it take several oscillations for the capacitor to charge fully?

2. Could there be any issue with waiting several oscillations for the capacitor to charge?

Generating a Uniform Magnetic Field

Motivation and Aim

A current carrying conductor generates a magnetic field according to the Biot-Savart law. In this experiment we measure the nature of the field produced by a circular coil of current and by pairs of coils arranged in Helmholtz and anti-Helmholtz configurations.

Apparatus

1. Helmholtz coils with stand
2. Power supply rated for 5A at 15V
3. Long measuring scale
4. Gauss probe to measure magnetic field

Procedure

Configure the power supply in the constant current mode: Turn the voltage control potentiometers to the maximum and the current control potentiometer to a minimum. The current through the external load can be increased by using the current control knob; the voltage will increase proportionately. The power supply will work in the constant current mode as long as the voltage remains below the compliance voltage of the power supply. Note that this point will be reached at a lower current for larger output resistance loads. Set the knob to output a constant current of 3.5 A.

Gauss Probe:

1. The gauss probe is a transverse probe; i.e. its flat plane has to be held perpendicular to the direction of the magnetic field.

2. It has a direction marked on it; a positive value indicates that the field direction is as marked, while a negative value indicates the opposite.

Measurement of magnetic fields:

1. All measurements are to be made along the axes of the coils

2. Measurements should be made in steps of 1 cm for 20 cm on either side of a single coil; and in between the coils in the two-coil configurations and up to 20 cm beyond them.

3. Measurements should be made with the probe parallel to the plane of the coils, and then with the probe turned perpendicular to the plane of the coils.

Single Coil Measurement

1. Feed the current into just a single coil

2. Determine the direction of the magnetic field and hence the direction of the current in the coils using the right hand rule.

3. Measure the magnetic field along the axis of the coil.

4. Repeat the entire procedure for the second coil.

Helmholtz configuration

1. The coils should be coaxial, separated by a distance equal to their radius and connected in series such that their currents flow in the same direction.

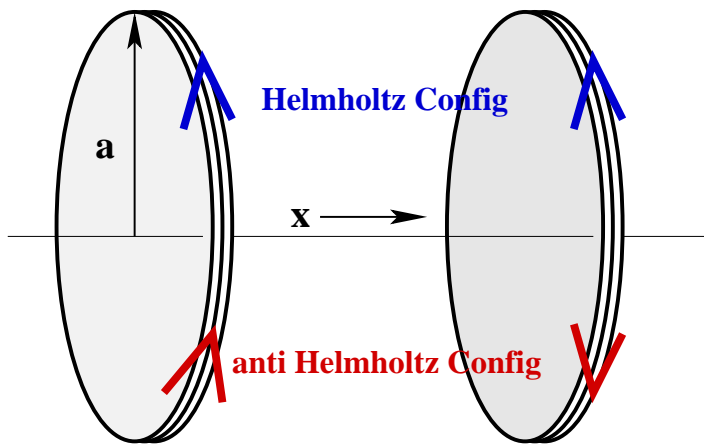2. Measure the axial profile of the magnetic field.

Figure 11: Coaxial coils separated by a distance equal to their radius form the Helmholtz (currents in the same direction — upper arrows) and anti-helmholtz configurations (currents in the opposite direction — lower arrows).

Anti-Helmholtz configuration

1. The coils should be coaxial, separated by a distance equal to their radius and connected in series such that their currents flow in opposite directions.

2. Measure the axial profile of the magnetic field.

Theory

The magnetic field along the axis of a circular current loop is given by

$$B = \mu_0 N I \frac{a^2}{2} \frac{1}{(x^2 + a^2)^{3/2}}$$

where, N is the number of turns in the coil, I is the current, a is the radius, and x is the axial distance. The direction of the field is given by the right-hand rule.

Analysis

1. Plot the magnetic field as a function of axial distance for all the configurations.

2. Determine the number of turns in each coil using the data for the single coil magnetic field. How do you confirm if it is correct?

3. Discuss the following in your lab report:

   (a) The gauss probe has a large least count - how would you improve the accuracy of the curves?

   (b) What is the significance of the Helmholtz configuration?

   (c) Compare the various plots - what does the difference between the Helmholtz and anti-Helmholtz configuration say about the magnetic field.

   (d) What is the effect of 3 sets of Helmholtz coils operating on the same bench?

Points to Ponder

1. . What will happen to the axial profile of the magnetic field in the Helmholtz and anti-helmholtz configurations if the coils are moved further apart?

2. What would the radial profile of the magnetic field be in the plane of the coils? In the mid-plane?

Force between magnets

Motivation and Aim

Like poles of magnets repel each other. How does the force between two magnets change as a function of their separation? In this experiment the force of gravity acting on one of the magnets is used to counterbalance the the magnetic force between two magnets.

Apparatus

1. A horizontal track

2. Non-magnetic clamps

3. A rolling platform

4. A pulley

5. A pan and a range of weights

Procedure

One magnet is clamped at a suitable position on the track such that the axis of the magnet is parallel to the track. The other magnet is fixed to the rolling platform. Make sure that the two magnet are axially matched and parallel to each other. Add a weight to the pan at the end of the string which runs over a pulley and let go of the platform. The platform will come to a standstill after a while. Measure the distance between the magnet faces. Repeat the procedure to ensure consistency in the readings. Perform the experiment with a different weight, and plot a graph between the balancing force and the separation at equilibrium between the magnets.
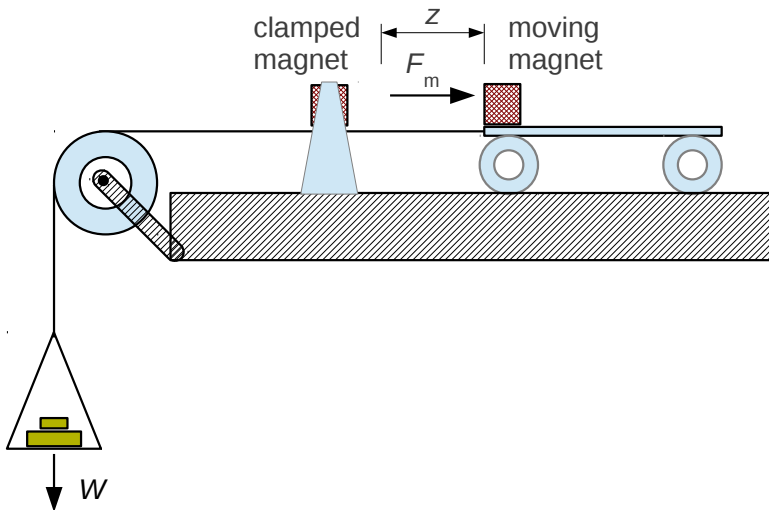

Figure 12: The track and pulley assembly for determining the repulsion between a pair of bar magnets. The magnets have a length (h) of 6.4 mm and a diameter ($2R$) of 12.7 mm.

Theory

The force between two cylindrical magnets placed end-to-end is given by

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

in which M is the magnetisation of the magnets, z is distance between the centres of the magnets (along the common axis) and h is the height of the cylindrical magnet. The magnetic flux density at the pole is given by $B_0 = \mu_0 M/2$. For separations much larger than the height, the first non-zero term in the bracketed expression is $6h^2/z^4$

Analysis

In this experiment the magnetic repulsion is balanced by the gravitational force via the tension in the string. Since the force of repulsion is roughly proportional to the inverse cube of the separation, it is necessary to measure the separation accurately. By choosing the weights in the pan carefully, it should be possible to study the accuracy of the the above formula. We may write the force on one magnet as arising due to the field of the other. If the test magnet is very weak (small M), then the method discussed here can be used to map the field (B) due to the 'source' magnet at different separations.

Points to ponder

1. How do you expect the force to vary at large separations?

2. What would be the limitations of the present scheme for estimating the force at large separations? At very small separations?

3. What is the reason for the oscillation and eventual slowing down of the motion of the platform?

4. If you were asked to determine the variation of the force between two charged plates instead of two magnets, how would you modify the apparatus?

Ballistic Galvanometer

Motivation and Aim

A primary, and direct method of measuring current is to exploit the force experienced by a current carrying conductor in a magnetic field and measure its deflection. This is the basis of a galvanometer (sometimes called a moving coil galvanometer), in which a the current to be measured is passed through a multi-turn, low resistance coil suspended in a uniform magnetic field. Because a coil like this has rotational inertia, its response to a current will depend on whether the current is steady or not. A galvanometer with a large rotational inertia and no damping is called a ballistic galvanometer. It is suited for measuring current *impulses* or charge, rather than steady currents, which in this experiment will be in the form of capacitor discharging. The deflection is usually measured by measuring the displacement of a beam of light reflected from a mirror attached to the suspension.

Apparatus

1. A moving coil galvanometer

2. A diode laser and ground glass scale arrangement on a pedestal

3. A steady current circuit

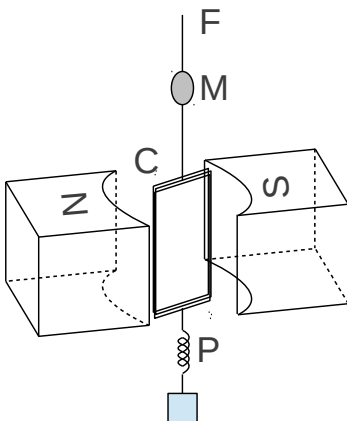4. A capacitor charging and discharging circuit

Figure 13: A ballistic galvanometer, showing the magnets, the coil, the suspension fibre and the mirror. Not shown is a soft iron cylinder which is placed inside the coil and coaxial with the fibre to ensure a uniform radial magnetic field in the cylindrical cavity.

Procedure

Attention   Be patient! This experiment requires you to be more careful and patient than other experiments in this course. Be on the watch out for unnecessary movements of persons and objects around you. Also note that the circuits given in this manual are simplified versions, meant only for an overview. You must refer to the instrument manual for details.

Adjust the lamp and scale such that incident beam, the reflected beam and the normal to the surface of the scale are coplanar. The galvanometer swing will take along time to dampen. Measure the resistance of the galvanometer coil (R_G).

Measurement of a steady current   Set up the galvanometer for the passage of a small current (of order 1 μA) using the given circuit and following the instructions in the galvanometer manual. Record the deflections for different values of the resistance R, repeating the measurement for each R thrice.

Measurement of charge from a capacitor   Using the given circuit charge a capacitor, by selecting a suitable charging voltage. Then switch the keys so that the capacitor discharges through the galvanometer and measure the throw of the light beam and the period of oscillation. Repeat a few times, waiting long enough in between to let the galvanometer dampen, and for the capacitor to re-charge.
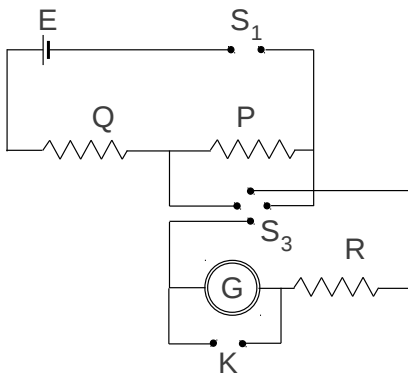
Figure 14: A simplified circuit for operating the ballistic galvanometer for steady current. Switch S_3 is used to reverse the current flow. Key K when shorted protects the galvanometer from damage due to a high current.
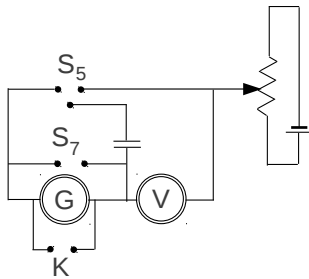

Figure 15: A simplified circuit for operating the ballistic galvanometer for measuring a capacitor discharge. Switch S_5 is used to select between charging and discharging, while S_7 is used to put the galvanometer into or out of the circuit.

Theory

For a steady current the restoring torque and the driving torque are related by $NABI = c\theta_0$. Here θ is the angular deflection from the stationary state, B is the magnetic field in which the coil is suspended, A is the area of the coil, N is the number of turns, I is the current, and c is the moment per unit twist of the galvanometer. Thus we can write $I = k\theta_0$, whence the galvanometer constant k is determined from the experiment.

When a charge Q, or a current impulse (current I flowing for a time ΔT) passes through the galvanometer, it results in a torque due the Lorentz force on the coil. The angular impulse is $NABI\Delta T$. If J is the moment of inertia of the coil, then then the resultant angular velocity ω_0 is given by $NABI\Delta T/J$, from which we get $Q = J\omega_0/NAB$. In terms of the galvanometer constant k, this becomes $Q = kT\theta_0/2\pi$. The the charge passing through the galvanometer can thus be determined by measuring the period of oscillation and the throw.

Analysis

Steady Current   Determine the current flowing for each setting of R, and plot the mean deflection vs. the current. Obtain the ballistic constant of the galvanometer from the slope of the graph.

Capacitor Discharge   From the known value of the capacitance, determine the charge sensitivity of the galvanometer using the formula $K = CV/\theta_0$, where V is the charging voltage, C is the capacitance and θ_0 is the deflection. Once the various constants of the galvanometer are determined, it can be used to measure any arbitrary (within a range) charge or current

Points to ponder

1. What is the minimum current needed to see any deflection at all?

2. What factors contribute to the swinging of the coil?

3. What would you do to isolate the galvanometer from vibrations?

Suggested Reading

Electricity and Magnetism *Chattopadhyay and Rakshit*, Chap. 12

Refractive Index of a Prism

Motivation and Aim

A ray of light incident on the surface of a prism undergoes reflection and refraction. (It may also get totally internally reflected.) The emerging ray and the incident ray are at an angle to each other – the angle of deviation. We study the variation of the angle of deviation as a function of the angle of incidence, in this experiment and deduce the refractive index of the prism material.

Apparatus

1. A sodium lamp
2. A rotating stage prism spectrometer
3. An equilateral prism
4.

Procedure

1. Let the sodium lamp warm-up for about 20 min.

2. Check for any loose fittings, and DO NOT force any screws!.

3. Level the spectrometer using the three base screws and a spirit level.

4. Familiarise yourself with all adjustments and check

   (a) Focusing the collimator and the telescope, adjusting the collimator slit
   (b) Locking and unlocking the prism table, the collimator and telescope arms, fine adjustments using the drive screw and reading out the angles

5. Set up the spectrometer for a parallel beam of light by the Schuster's method

6. Determine the angle of minimum deviation from the optimum positions of the telescope and the collimator.

Schuster's method   Set the collimator slit to be fairly narrow. Adjust the prism position so that the slit image is seen through the telescope. Make sure that the height of the prism table is appropriate. As the prism table is rotated slowly in one direction, the the image of the slit co-rotates up to a certain position and then its direction of motion reverses. Successive views of the image as the prism table is rotated slowly (in the same direction), are shown in the figure. The position of the prism corresponding to the view (c) is the position of minimum deviation. The telescope is clamped in that setting. Next (by using the tangential screw) the prism table is rotated to a position of slightly greater deviation than the minimum deviation position (this corresponds to a slightly larger angle of incidence). The screw is worked till the image of the slit comes to the edge of the field of view as in position (a), where it appears blurred (if the telescope is not properly focused). The telescope is adjusted to get a fine slit image. The table is then turned in the opposite direction (again using the tangential screw) and the image moves back gradually to the minimum deviation position and back the edge of the field of view (e). In position (e) the image may appear blurred. This time the collimator is adjusted to get a sharp well defined image. The back-and-forth rotation accompanied
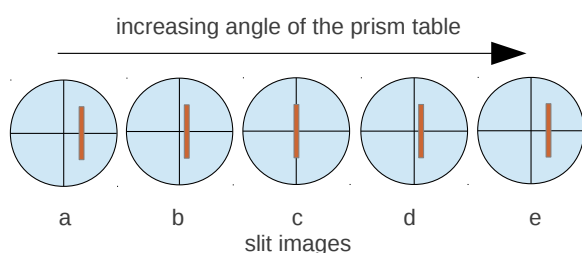
Figure 16: Series of images observed when carrying out Schuster's procedure for setting up a parallel beam. The spectrometer is operated close to the angle of minimum deviation (image c corresponds to this setting).

by alternate adjustment of the collimator and the telescope is repeated a few times, until a sharp image is seen throughout the field of view.

Theory

The angle of deviation does not change as rapidly as the the change in the angle of incidence itself and there is a certain minimum deviation associated with every prism geometry. For a symmetric prism the minimum deviation occurs when the angle of incidence and emergence are equal. In this configuration, the refractive index of the prism can be determined rather accurately, as the angle of minimum deviation is a slow varying function. For equal incidence and emergence angles, the angle of minimum deviation δ, the apex angle of the prism α, and the refractive index n are related by

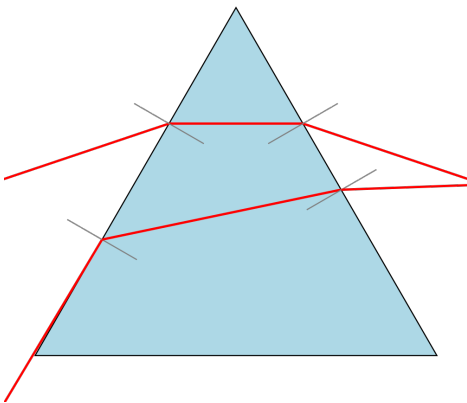$$n = \sin[(\delta + \alpha)/2] / \sin(\alpha/2)$$

Figure 17: The change in the angle of deviation for different angles of incidence. The symmetric case gives the minimum angle of deviation.

Analysis

Determine why there should be an angle of minimum deviation by writing down the relationship angles of incidence, emergence, deviation etc. with a aid of a detailed ray diagram.

Points to ponder

1. What would the image appear as if the sodium lamp were replaced by a mercury lamp, or an ordinary incandescent lamp?

2. How is the angle of minimum deviation related to the observation of a rainbow?

Inverse square law of light intensity

Motivation and Aim

The intensity of light (energy received per unit area) at a distance from a source of light falls with the distance. In this simple experiment we determine the rate at which the intensity reduces with the distance.

Apparatus

1. An incandescent lamp with aperture
2. An energy calibrated photodiode and readout
3. An optical rail
4. A few apertures

Procedure

1. Set the lamp at one of the rail and measure the intensity falling on the detector for different separations between them.

2. Plot the intensity (or the value of the photodiode signal) as a function of distance

3. If you observe anything unusual about the graph, try to determine why this happens, and find a remedy.

Theory

The intensity is expected to fall of as inverse square of the distance from the source – this is a simple fallout of the fact that the area of an imaginary sphere illuminated by a point source increases as r^2.

Analysis

Determine why you do not see a straightforward r^{-2} behaviour in this case. Note that we do not have a point source. Repeat the experiment by using a fine slit or aperture in front of the source. Also analyse whether the finite detector area affects your result.

Points to ponder

1. How does the ambient light influence your measurements?

2. What would you do if the detector signal reaches a maximum value (saturates) as you reduce the distance between the source and the detector?