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COURSE I PHYSICS LABORATORY

PRACTICALS - PART I



**DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN**

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PRACTICALS - PART I**

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1 Hooke's Law (Behaviour of Spiral Spring under Action of Applied Force)

NOTE:

The 'deliverable' for this practical is a full write-up to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on tabulating results and drawing graphs. This week there is no need to perform any uncertainty analysis, but students should pay some attention to the significant figures they use to record their readings. Early in the semester a lecture will be devoted to uncertainty analysis, and all subsequent practicals will require a treatment of uncertainties.

PRE-PRAC QUESTIONS

Since this practical runs from the first day of the semester, there are no pre-prac questions for this activity. However, for future practicals, you will be required to submit solutions to several pre-prac questions via VULA at the START of your laboratory session.

1.1 Aim

The aim of this experiment is to determine the relationship between the extension of a spiral spring and the magnitude of the applied force causing the extension. In carrying out the exercise, we hope to introduce students to the use of tables and graphs in experimental reports.

1.2 Introduction

It is well known that the application of a force to a spiral spring will cause the spring to stretch. Common sense tells us that the greater the applied force the greater the extension of the spring (i.e. the amount by which the spring is stretched). What is not clear is whether there is a direct relationship between the applied force and extension of the spring, i.e. whether doubling the applied force doubles the extension. This is easiest tested by plotting a graph of the extension of the spring (dependent variable) against the applied force (independent variable). If the extension is directly proportional to the applied force we should obtain a straight line passing through the origin.

1.3 Apparatus

You are supplied with a spiral spring suspended from a retort stand, a small bucket, a number of ball bearings of known mass, and a metre stick.

1.4 Measurement of force and extension

In this experiment a force is applied to the spiral spring by hanging a mass m onto the end of the spring. The force exerted on the spring is just mg and the extension produced by the applied force can easily be measured with the aid of the metre stick.

Begin by attaching the bucket to the end of the spring and reading the position of the pointer fixed to the end of the spring. We shall consider this position as the “zero position”. Now add the ball bearings one at a time, reading the new position of the pointer. Hence, determine the extension produced by the weight of the ball bearings. Use a ball bearing mass of 13.7 grams and take $g = 9.80 \text{ m/s}^2$ to determine the weight of the balls in the bucket. If you have time, use one of the triple-beam balances to confirm the mass of the ball bearings.

1.5 Tabulation of your data

Tabulate your results as shown below, taking care to record the appropriate number of *significant figures*. For example:

MASS OF EACH BALL BEARING: 13.7 g

TABLE 1.1: APPLIED FORCE AND SPRING EXTENSION

No. of Ball Bearings	Force (N)	Pointer Position (cm)	Extension (cm)
0	0.000	43.6	0.0
1	0.134	41.2	2.4
2	0.268	38.9	4.7
...			

Remember to record *all* readings that you have taken. The reason for tabulating your results is for neatness and for efficiency. You need only indicate the units once in the heading and it is immediately clear that all readings in the same column are measured in that unit. Any reading that does not vary (e.g. the mass of each ball bearing) should not be recorded in the table, but reported separately.

Read through Section C4 of the “*Laboratory Guide to Measurement, Analysis and Reporting*” and make sure that you are able to explain the number of significant figures chosen for each entry in the above table, and apply the same reasoning to your own table.

1.6 Plotting your graph

Plot a graph of extension versus force. From the form of the graph you should be able to determine whether the extension is, or is not, directly proportional to the applied force. If you obtain a straight-line graph passing through the origin, the extension *is directly proportional* to the force exerted on the spring. If the graph is a straight line but it does not pass through the origin, then the graph indicates that the extension is linearly related (*but not directly proportional*) to the applied force. Be sure to draw the best straight line through the plotted points—do not try to force your graph through the origin and do not “join the dots”!

Check that you have labelled your axes (and indicated the units of measurement) and given your graph a suitable heading. A heading such as “GRAPH OF EXTENSION VS FORCE” is pointless, as a quick glance at the axis labels would have told one that. What is the extension of? Why was the experiment carried out? A more informative heading would be something like “GRAPH OF SPRING EXTENSION VS APPLIED FORCE TO ESTABLISH THEIR RELATIONSHIP”.

Finally, once one has established that extension is indeed proportional to the applied force, the constant of proportionality can be obtained from the slope of the straight-line graph. Measure the slope of your graph by choosing two convenient points on the best-fit line. Remember to choose points sufficiently far apart and *not to use any of the actual plotted (i.e. data) points* when calculating the slope.

For this practical we will stop here, but your attention is drawn to the fact that in experimental work, a result for a measurand (the constant of proportionality in this case) is incomplete unless it includes an uncertainty. In future, after some instruction on uncertainty analysis, you will be expected to perform a complete determination of a measurand, which will include finding the uncertainty in the measurement.

2 Data Analysis

NOTE:

*This activity involves analysing a set of data and performing a Type A uncertainty analysis. Depending on the course for which you are registered, this activity will either be done in class or else in a laboratory session. In both cases, a separate exercise sheet will be handed out at the start. Hand-in details will be discussed at the session. In preparation, students should carefully read through Section A (page 3 to 13) of the “**Laboratory Guide to Measurement, Analysis and Reporting**”.*

3 The Simple Pendulum

NOTE:

The 'deliverable' for this practical is a full write-up to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on using Excel to plot a graph and perform a Type A uncertainty analysis.

3.1 Aim

The aim of this practical is to investigate the relationship between the period and length of a simple pendulum, and hence determine the acceleration due to gravity g . In carrying out this exercise, we hope to demonstrate the usefulness of spreadsheets as well as provide students with an opportunity to perform a Type A uncertainty analysis.

3.2 Introduction

Excel is a very powerful and useful tool for data handling and all students should know how to use the package. In this practical, we use the simple pendulum experiment to introduce students to the use of Excel. At the same time, we will be applying our recently acquired knowledge of how to treat data with scatter to determine the uncertainty in our measurand, thereby allowing us to establish whether our measured g agrees with the accepted result or not.

A pendulum consists of a bob (a mass) attached to a string that is fastened so that the pendulum can swing or oscillate in a plane. For a simple pendulum, all of the mass is considered to be concentrated at the centre of the bob. Experimentally it is found (you may wish to confirm this yourself) that the period of the pendulum is independent of the mass of the bob and the angle through which it swings (provided that the angle is not too large, i.e. $\theta \leq 15\text{-}20^\circ$). The period of a simple pendulum depends only on the length of the pendulum, viz.

$$T = 2\pi\sqrt{\frac{L}{g}}.$$

If the period of the pendulum is measured for a variety of lengths, a plot of T^2 vs L will produce a straight line passing through the origin with gradient $4\pi^2 / g$, allowing one to determine g from the gradient.

Alternatively, one can rearrange the equation so that it becomes

$$g = 4\pi^2 \frac{L}{T^2},$$

and use this to determine g for each set of values of L and T . Since there is likely to be some scatter in the data, it is unlikely that you will obtain the same value of g for each set of readings. The most reliable value for g will naturally be given by the average of your individual values, while the uncertainty is given by the standard deviation of the mean, $s(\bar{g})$.

3.3 Method

Set up the pendulum using the metal bob and string length of about 1 metre. Set it swinging in small oscillations (a pendulum's oscillations are described as “*small*” if the angle of oscillation, θ , is 20° or less). When measuring the period T of the pendulum it is always more accurate to time several successive oscillations together, and divide by their number to obtain the time taken for a single oscillation. Taking 20 seconds per measurement is not unreasonable. Observe the oscillations and then decide how many oscillations you should time.

You are now in a position to carry out the detailed investigation of the relationship between period and length, and to determine g . Measure the period T for 8 different values of L , taking at least 3 readings for each. Cover a wide range of lengths from about 0.5 m to 1.5 m.

3.4 Analysis

Initiate Excel by clicking on the Excel shortcut on the computer's desktop. The use of Excel for data analysis is discussed in Section D1 of the “*Laboratory Guide to Measurement, Analysis and Reporting*”, so only points relevant to this practical will be discussed below. An example of how your printout should look is included at the end of the description for this practical.

For your convenience, an Excel file called pendulum.xls has been placed on the hard disk of the laboratory PCs. You may set up your own Excel tables, or you may make use of the template provided. **If you make use of the template, you should immediately save it under some other name, e.g. you and/or your partner's initials.**

Insert your length reading in the first column and the time for your observed oscillations (perhaps 20) in the next three. Try to use Excel to do all your calculations by clicking on the cell where you want the answer to go, and typing = followed by the formula and the cell #'s to which you wish the formula to be applied. Use your L and T values to calculate g for each set of

readings by entering the appropriate formula. You will need to adjust the number of decimal places in the various columns to reflect the correct number of significant figures.

Now use Excel to plot a graph of T^2 vs L . Transfer your data to the table on the upper right, highlight the two columns of data you wish to plot, and then use **INSERT, CHART** to call up the chart (plotting) procedure. Now follow the instructions given in Section D1 of the “*Laboratory Guide to Measurement, Analysis and Reporting*”. To draw the best straight line through your points, click somewhere inside your graph to select it, then click on **CHART, ADD TRENDLINE** and select the LINEAR option. To display the value of the slope and intercept of this straight line, click on **OPTIONS** and check the DISPLAY EQUATION ON CHART box.

Next use Excel to calculate your average value of g and the uncertainty in this value. Begin by transferring your 8 values of g to the bottom table. Then find the sum and the average of these 8 values. By subtracting the average value, \bar{g} , from each value of g , determine the deviation of each value from the mean. To confirm that your calculations are correct so far, check that the sum of the deviations is zero. Finally square these deviations, find their sum, and use this to calculate the standard deviation, $s(g)$, and the standard deviation of the mean, $s(\bar{g})$: the uncertainty, $u(\bar{g})$, in this case from the Type A analysis.

Note: Save your work and then print it out. Write up your practical in the usual manner, pasting the printed Excel spreadsheet under the RESULTS section.

In your conclusion you will need to confirm whether your measured g agrees with an accepted result of $(9.80 \pm 0.02) \text{ m/s}^2$ (see Section B of the “*Laboratory Guide to Measurement, Analysis and Reporting*”). Once one has calculated the uncertainty, one is able to state that there is a 68% probability (approximately) that the measurand g lies in a range from $\bar{g} - u(\bar{g})$ to $\bar{g} + u(\bar{g})$. If this interval overlaps at all with the interval of the accepted result, we are able to say that our measurement agrees with the accepted result “*within the stated experimental uncertainty*”. Otherwise, we have to conclude that our measurement probably does not agree with it.

Remember that the calculation has only taken the uncertainty associated with the scatter in the data into account (i.e. a Type A evaluation), and there may well be other sources of uncertainty that affected your result. Therefore, if the measured g does not agree, one should try to think of other possible sources of uncertainty that could have affected your result (e.g. the timer might have been running systematically fast). Decide whether your measured result agrees with the accepted result and comment on the possible source of any discrepancies.

Pendulum Sample Spreadsheet

Table 1: Measurement of period of simple pendulum at different lengths to determine g

L (m)	10 T (s)			T(av) (s)	T ² (s ²)	g (m/s ²)
0.495	14.26	14.28	14.31	1.428	2.040	9.581
0.706	16.95	16.94	16.97	1.695	2.874	9.700
0.897	19.33	19.19	19.24	1.925	3.707	9.555
1.103	21.36	21.42	21.39	2.139	4.575	9.520
1.295	23.20	23.03	23.08	2.310	5.338	9.581
1.503	24.86	24.85	24.58	2.476	6.132	9.679

L (m)	T ² (s ²)
0.495	2.040
0.706	2.874
0.897	3.707
1.103	4.575
1.295	5.338
1.503	6.132

Table 2: Calculation of standard deviation of g

g (m/s ²)	δ (m/s ²)	δ^2 (m ² /s ⁴)
9.581	-0.021	0.0005
9.700	0.097	0.0095
9.555	-0.047	0.0022
9.520	-0.083	0.0069
9.581	-0.022	0.0005
9.679	0.076	0.0058
sum	57.616	0.000
average	9.603	0.0253

$$\delta = (g - \bar{g})$$

where

$$s(g) = \sqrt{\frac{\sum(g - \bar{g})^2}{n-1}} = \sqrt{\frac{\sum\delta^2}{n-1}}$$

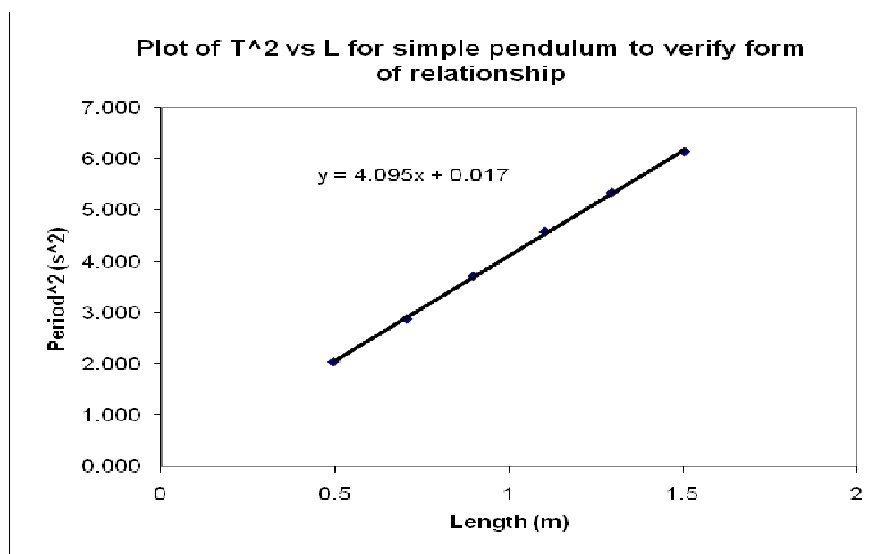
$$u(\bar{g}) = s(\bar{g}) = \frac{s(g)}{\sqrt{n}}$$

standard deviation of g
standard deviation of mean

$$s(g) = \boxed{0.071}$$

$$s(\bar{g}) = \boxed{0.012}$$

$$g = 9.603 \pm 0.012 \quad \text{m/s}^2$$



4 Normal Distribution

NOTE:

*The ‘deliverable’ for this practical is an abridged write-up (**containing just the Results, Analysis and Conclusions**) to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on observing and quantifying the scatter in a set of readings to illustrate the ideas crucial to Type A uncertainty analyses.*

4.1 Aim

The aim of this experiment is to (i) investigate random fluctuations in observations of the decay rate of a radioactive source, to (ii) determine the frequency distribution of these fluctuations and to (iii) estimate the standard deviation of the observed decay rate. In carrying out this exercise, we hope that students will consolidate their understanding of uncertainty due to scatter in measurement.

4.2 Introduction

Science and engineering students will generally find that data acquired in experiments will exhibit considerable variation or scatter. How to treat this variation or “*uncertainty*” is therefore of great importance. One area in physics where significant scatter in data is observed is in radioactive decay, and so an experiment involving radioactive decay is an ideal experiment to introduce first-year students to the methods required for the treatment of uncertainty in data.

Radioactive decay is a process in which an unstable atomic nucleus changes to a more stable form. The decay is usually accompanied by the emission of radiation (e.g. α , β or γ), which can be observed by means of a Geiger counter. Each unstable nucleus has a definite probability for decaying in any one-second interval. If we knew both this probability (for the particular unstable nuclear species) and the number of unstable nuclei in our radioactive source, then we could calculate the expected average number of decays in that source in one second. However, each nucleus decays at a random time so that the number of decays per second we can expect to obtain is spread over a range of values, extending above and below the average value. A plot of these values in the form of a histogram will indicate the frequency distribution of the observed decay rate.

The form of this distribution can be predicted from theoretical considerations. Since radioactive decay is a random process, it can be shown that a histogram consistent with the “normal” or “Gaussian” distribution should be observed, provided the number of decays which are registered in each measurement is sufficiently large (i.e. >20). The first objective of this experiment is to check whether the frequency distribution of a set of count rate measurements, obtained under identical conditions, is consistent with the predicted Gaussian form. Random variations or uncertainties of one kind or another are encountered in virtually every experimental measurement. Therefore, the distribution which you observe in this experiment with the radioactive source is typical of what you must expect in all other experiments.

To express the estimated extent of random uncertainties, we use the concept of *standard deviation*. The second objective of this experiment is to compare the standard deviation of your result obtained by two different methods, viz. graphically and by detailed calculation.

It will be reported later that it is also possible to estimate the standard deviation of a random process, such as radioactivity, from a single reading. The third objective is therefore to compare the standard deviation obtained in this manner with those obtained by the other methods.

4.3 Apparatus

A radioactive source (^{60}Co) is provided together with a Geiger counter and a scalar unit including a built-in electronic timer. The Geiger counter will be set up and checked for you in advance, by a demonstrator, so that you will not have to spend time adjusting the operating conditions.

4.4 Measurements and analysis

The count rate recorded by the Geiger may be adjusted by varying the distance between it and the ^{60}Co source. Adjust this distance until the counts recorded in a timing interval of 10 s number between 400 and 500. Ensure that the source does not move during the remainder of the experiment. *You must also make sure that the voltage reading on your Geiger counter does not drift during the practical*, as this could affect the count rate.

Using a timing interval of 10 s, take 100 or more independent readings of the count recorded by the Geiger. These readings must be neatly tabulated, e.g. in a table of 4 columns with each column containing 25 numbers. Plot the readings in a histogram using a bin width of 10 counts. Draw a “best-fit” smooth Gaussian-like curve through your histogram.

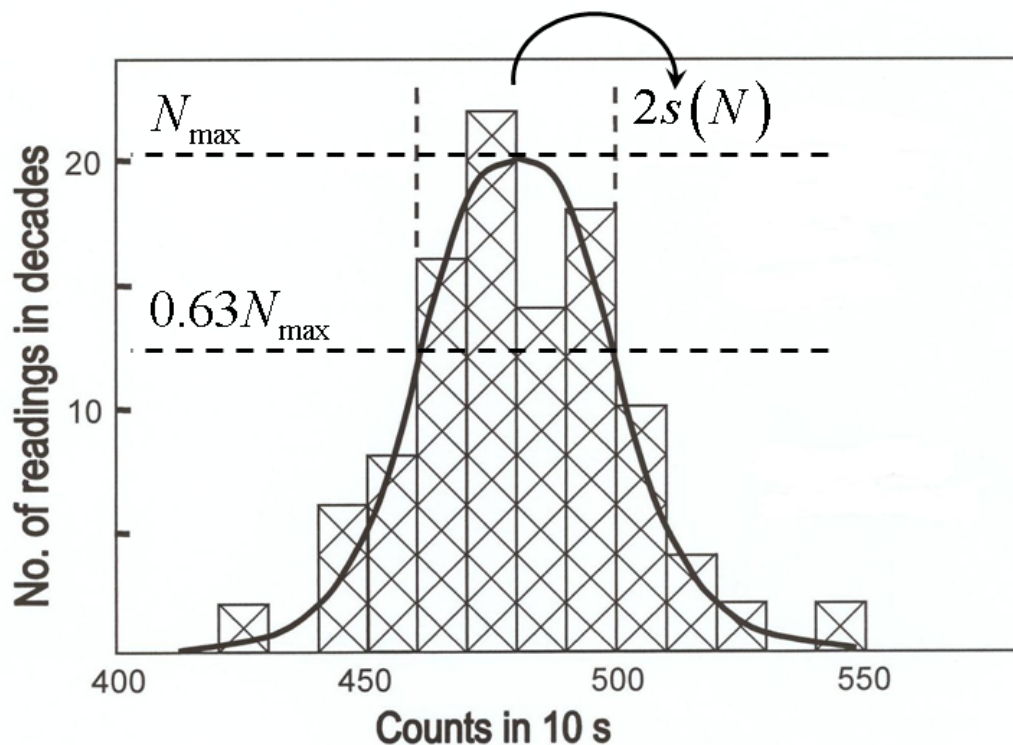


Figure 4.1 Histogram of readings and best-fit Gaussian curve

A working criterion for obtaining a best-fit is that vacant area (i.e. area unfilled by histogram) below the curve should be *approximately equal* to the filled area extending above the curve. The best-fit should also be symmetric about the mean.

The spread in the single count readings can be quantified by the standard deviation, $s(N)$, which can be estimated by various methods.

- First, determine the standard deviation, $s(N)$, graphically from the width of the best-fit Gaussian curve drawn through your histogram at 63% of its maximum height (see Section A2 of the “**Laboratory Guide to Measurement, Analysis and Reporting**”).
- Next, determine $s(N)$ using the statistical package on your calculator.

How do your two values for standard deviation, $s(N)$, compare?

As pointed out in Section A2 of the “**Laboratory Guide to Measurement, Analysis and Reporting**”, approximately 2/3 of your readings should fall between (measured mean - $s(N)$) and (measured mean + $s(N)$). Determine how many of your readings fall in this range and check if

this does correspond to about 2/3 of your readings. Since it is sometimes difficult to draw the correct Gaussian curve through a histogram containing only 100 readings, the value of the standard deviation determined using your calculator is probably the most reliable and it is therefore best to use this value to determine the range.

The standard deviation of the mean, $s(\bar{N})$, of the 100 observed counts (per 10 s) should also be determined. Since you have determined $s(N)$ in two ways, you will also have two values for $s(\bar{N})$. What information does the standard deviation of the mean convey? In other words, what can you say about the interval (measured mean - $s(\bar{N})$) to (measured mean + $s(\bar{N})$)?

- Finally, it can be shown for the radioactive decay process that the standard deviation can be roughly estimated from the simple equation

$$s(N) = \sqrt{Count} ,$$

where *Count* here is the number of decays recorded for a "typical" 10 s reading. Use this method to obtain an estimate for $s(N)$ and compare it with the values that you obtained by the other two methods. What do you conclude?

5 Motion under Free Fall

NOTE:

*The ‘deliverable’ for this practical is an abridged write-up (**containing just the Results, Analysis and Conclusions**) to be handed in by 5:00 pm on the day of the practical.*

In this practical, the emphasis is on determining uncertainty from a Type B evaluation, uncertainty propagation and quoting the result of a measurement in the standard way (recall that making a measurement in the laboratory involves obtaining both the best approximation to the value of a measurand as well as its uncertainty).

5.1 Aim

The aim of this experiment is to measure g , the acceleration due to gravity, by using an apparatus to time the free-fall of a ball bearing over a known distance. In carrying out the exercise, we will demonstrate how non-linear relationships can sometimes be manipulated into a linear form, thus making the plotting and analysis much easier. Students will also have the opportunity to perform a Type B uncertainty analysis.

5.2 Introduction

We saw in the Hooke’s Law Experiment that the linear relationship between the force on the spring and the resulting extension resulted in a straight-line graph when the extension was plotted against the force. Straight-line relationships are convenient because:

- they can be easily tested,
- it is easy to find the “best-fit” straight line, and
- physical quantities may often be determined from the slope and/or intercepts on the axes.

If we know (or suspect) the form of a non-linear relationship, we may be able to choose our variables in such a way that the resulting graph is a straight line. For example, if our relationship is of the form $y = ax^2 + bx$, a graph of y vs x will not be a straight line, but a graph of y/x vs x will be a straight line (with slope a , and intercept b). We will illustrate this by means of this free-fall experiment.

5.3 Theory

For an object falling free (ignoring air resistance) we know that

$$x = ut + \frac{1}{2}gt^2.$$

In this experiment, u is the speed of the ball when the timer starts. If the timer starts as soon as the ball is released, then $u = 0$.

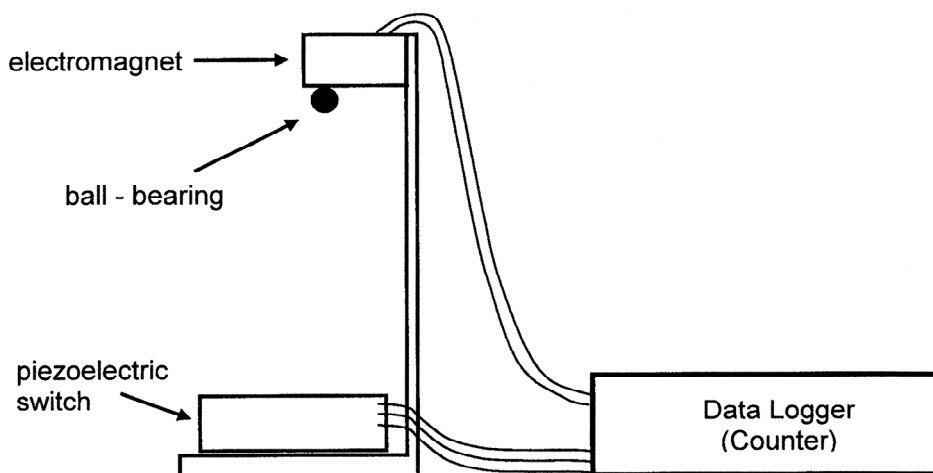
Clearly a graph of x vs t will not give a straight-line graph. However, dividing both sides of the equation by t gives:

$$\frac{x}{t} = u + \frac{g}{2}t,$$

and a plot of x/t vs t should therefore give a straight-line graph with gradient of $g/2$ and an intercept of u . If the timer does indeed begin timing as the ball is released, the graph will pass through the origin – if not, there will be an offset.

5.4 Apparatus

The layout of the apparatus for this experiment is illustrated schematically below. It is not necessary to set it up; this should already have been done. When START is selected on the data-logger, the timer is activated and the ball is released. The “stop” switch is a piezoelectric switch moulded into the platform at the bottom of the retort stand. This piezoelectric switch is activated by the impact of the falling ball.



The operation of the data-logger and free-fall apparatus is discussed overpage.

Device	Action	Result
STEP 1		
DATA-LOGGER	<i>Switch-ON</i> ... and wait for the "Scrolling Instruction Screen".	
INTERFACE-UNIT		Led lights-up and remains ON . Has no further "visible" roll.
RELEASE UNIT		After some seconds, the GREEN & BLUE led's give short flashes. This means that the Release Unit is READY and waiting for a ball.
STEP 2		
DATA-LOGGER		Scrolling Instruction Screen instructs operator to insert ball and press the RESET/CLEAR switch.
RELEASE UNIT	<i>Insert ball.</i>	GREEN led lights-up. ... after a second, the BLUE led also lights-up.
STEP 3		
DATA-LOGGER	<i>Press</i> the RESET/CLEAR switch.	Screen instructs operator to press the START switch.
RELEASE UNIT		GREEN & BLUE led's are ON .
STEP 4		
DATA-LOGGER	<i>Press</i> the START switch.	Screen goes blank
RELEASE UNIT		Ball is released.
PIEZO SENSOR		BLUE led in recess under PVC surface flashes briefly as ball hits surface.
DATA-LOGGER		Screen displays Fall-Time in seconds.
STEP 5		
EITHER:		
DATA-LOGGER	<i>Press</i> the RESET/CLEAR switch to clear the <i>Data Logger</i> screen.	Screen goes to scrolling instruction mode.
RELEASE UNIT		GREEN & BLUE led's start flashing briefly after a few seconds.
The unit is now ready for a repeat of the experiment – Go To Step 2		
OR:		
RELEASE UNIT	<i>Insert ball.</i>	GREEN & BLUE led's start flashing alternately in an alarm state.
DATA-LOGGER	<i>Press</i> the RESET/CLEAR switch to clear the <i>Data Logger</i> screen.	
RELEASE UNIT		GREEN led start flashing briefly.... after a second, the BLUE led also flashes briefly, to indicate the the unit is now ready for a repeat.
The unit is now ready for a repeat of the experiment – Go To Step 3		

5.5 Method

Read the time, t , taken for the ball to fall a distance x . Repeat the fall at least three times through the distance x and determine the mean of the time readings. Report all readings; distance, time and average time in a table. Repeat the exercise until you have five or six readings over a range of x values between 0.1 and 0.7 m (approximately). Note that x is the distance the ball falls. Since the timer is stopped by the BOTTOM of the ball, from where should you measure x ? Considering the equipment used to measure the distance fallen by the ball, to how many decimal places should your x reading be quoted (when expressed in metres)?

Plot a graph of x/t vs t to confirm that your graph is a straight-line graph. Determine your best approximation to the value of g from the slope of your best-fit line to the plotted data. What do you think are the sources of uncertainty in this experiment? Draw up an uncertainty budget. You will probably agree that a major source of uncertainty in g is the drawing of the best-fit by eye. Considering extreme best-fits, determine the uncertainty in the slope of the graph (a Type B evaluation, as discussed in Section B1 of the “*Laboratory Guide to Measurement, Analysis and Reporting*”). Combining all uncertainties, calculate the uncertainty in g .

Quote the result for your measurand g in the usual way (i.e. best approximation \pm uncertainty). Is your measured g a reasonable one, i.e. how does it compare with the accepted result of $(9.80 \pm 0.02) \text{ m/s}^2$? If your measured g does not agree within uncertainty with the accepted result, can you suggest possible reasons why? Is there evidence that the timer started immediately on release of the ball?

6 SHM

NOTE:

*The ‘deliverable’ for this practical is a full write-up to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on using Excel and Curfit to perform least-squares fitting to data. The method of least squares is covered in Section B2 of the “**Laboratory Guide to Measurement, Analysis and Reporting**” – you MUST read this section before coming to the practical.*

6.1 Aim

The aim of this experiment is to investigate the relationship between the period of oscillation of a mass on a spring and the magnitude of the mass, and hence determine the spring constant, sometimes also referred to as the force constant, of the spring from the slope of a graph. In order to determine the uncertainty in your value of the spring constant, you will need to determine the uncertainty in the slope of the graph using the method of least squares. The calculation is quite involved and is therefore best handled by use of an Excel spreadsheet, or else done automatically by the Curfit plotting program.

6.2 Introduction

In the Hooke’s Law experiment, the effect of adding different masses to a spring was investigated. The extension of the spring is given by Hooke’s law

$$F = k x,$$

where F is the applied force, x is the extension of the spring, and k the spring constant.

If a mass hangs at rest at the end of a spiral spring, and the upward force exerted by the spring on the mass exactly balances the downward gravitational force acting on the mass, the mass is said to be in ‘equilibrium’. We thus refer to this position as the equilibrium position.

If the mass attached to the spring is now pulled downward from its equilibrium position, the force exerted by the spring on the mass is increased. Since the gravitational force acting on the mass is unchanged, the net force acting on the mass is now in an *upward* direction. If, on the other hand, the mass is displaced in an upward direction from its equilibrium position, the force

of the spring on the mass is decreased, and the net force on the mass is in a *downward* direction. Thus, if the mass is pulled down slightly from its equilibrium position and released, it will oscillate about its equilibrium position, because when it is below it the net force is in an upward direction, while, if it is above it, the net force is in a downward direction. The net force, therefore, always acts to try and restore the mass to its equilibrium position. However, the mass overshoots the equilibrium position each time! Such motion is called “simple harmonic motion” (SHM). For such simple harmonic motion, the period, T , is given by:

$$T = 2\pi\sqrt{(m/k)}. \quad \text{Eq. 6-1}$$

Of course, the spring is also undergoing oscillations, and if it has a non-negligible mass m' , this will also affect the period of oscillation. We can, however, correct for this effect by replacing m in Eq. 6-1 by the effective mass M , given by:

$$M = m + \frac{1}{3}m'. \quad \text{Eq. 6-2}$$

The period of oscillation is then given by:

$$T = 2\pi\sqrt{(M/k)}. \quad \text{Eq. 6-3}$$

6.3 Method

Use the triple beam balance to determine the masses of the four cylinders and the mass of the spring. Attach one of the cylinders to the spring, pull it down slightly and set it oscillating. Measure the time taken for 20-30 oscillations and repeat three times. Replace the cylinder by another cylinder and repeat until you have all four readings. Since at least 5 or 6 readings are normally required for a straight-line graph, use combinations of masses to make up two more readings, thereby giving a total of six readings.

6.4 Analysis

To simplify the manipulation of the data, Eq. 6-3 can be linearised by squaring both sides to obtain:

$$T^2 = \frac{4\pi^2}{k}M. \quad \text{Eq. 6-4}$$

A plot of T^2 vs M will therefore produce a straight-line graph with a slope of $4\pi^2/k$, thus allowing the determination of k from the slope of the graph. In the Hooke's Law experiment, a best-fit to linear data was drawn by eye. In this practical, we will use a more sophisticated approach: the method of least squares.

For ease of use, an Excel file called SHM.xls has been placed on the hard disk of the laboratory PCs. Initiate Excel by clicking on the Excel shortcut on the computer's desktop. You may design your own tables, or you may make use of the template SHM.xls. **If you use the template, remember to immediately save it under some other name, e.g. you and your partner's initials.**

Insert your mass reading in the first column and the time for your 20-30 oscillations in the next three. Try to use Excel to do all your calculations. Remember to adjust the number of decimal places in the various columns to reflect the correct number of significant figures (see Section D1 of the "*Laboratory Guide to Measurement, Analysis and Reporting*" for details).

Plot a graph of T^2 vs M using Excel, remembering to get Excel to display the slope of the graph by clicking on OPTIONS and checking the DISPLAY EQUATION ON CHART box. You will use the slope of the graph later on to determine your value of the spring constant k . Excel actually uses least squares to evaluate the slope and intercept of the best-fit line.

Next you need to determine the uncertainty in the slope of your graph, so that you can determine the uncertainty in k . This is again found by the method of least squares. If you are using the template, the table to be used for this least squares exercise can be found on sheet #2 of your workbook (which you can call up by clicking on SHEET2 at the bottom of your spreadsheet). You should find that your values for T^2 and M have been automatically transferred from SHEET1 but, if not, transfer them manually.

The four equations which are to be used to calculate the slope and intercept, and the uncertainty in the slope and intercept can be found in Section B2 of the "*Laboratory Guide to Measurement, Analysis and Reporting*". As they are all rather complex equations, it is easier, especially when using Excel, to simplify the equations by introducing an intermediate step in the calculation. In our case, the four equations to be used can be simplified by defining two quantities, namely:

$$\alpha = \frac{\sum d_i^2}{(n-2)},$$

and

$$\beta = n \sum x_i^2 - (\sum x_i)^2,$$

where d_i is the “deviation” of each point, i.e. $d_i = y_i - (mx_i + c)$, and n = the number of readings.

The four equations then become

$$m = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{\beta},$$

$$c = \frac{\sum x_i^2 \sum y_i - \sum x_i y_i \sum x_i}{\beta},$$

and

$$\Delta m = \sqrt{\frac{n\alpha}{\beta}},$$

$$\Delta c = \sqrt{\frac{\alpha \sum x_i^2}{\beta}}.$$

Complete the table by inserting the appropriate calculation in each cell of the table. Get Excel to calculate your values of α and β , and then use these values to calculate the slope m , the intercept c , and the uncertainties Δm and Δc .

There are a number of checks that you can do to ensure you keep on track as you go along. Your first check is to ensure that the values you calculate for the slope m and the intercept c agree with those shown on the Excel plot. The next check is that the sum of the deviations d_i should equal zero. Finally, check that your answers for the uncertainties Δm and Δc are correct by calling up the *Curfit* program on your PC (see Section D2 of the “**Laboratory Guide to Measurement, Analysis and Reporting**”). This is a plotting programme which fits a least squares line to data. Insert your values into the table, plot a graph, and then check that your calculated Excel values agree with those given by the *Curfit* plotting program. If they don’t, you should check that the Excel formulae you used for the calculation of α , β , Δm and Δc are correct. Once you are convinced that your calculations are correct, print out both spreadsheets on the laboratory printer, making copies for your partners. **NOTE: save your work before trying to print.**

Use the value for the slope of the graph and its uncertainty to determine your result for the spring constant (i.e. $k \pm u(\bar{k})$). How does your result compare with that obtained in the Hooke's Law experiment? Write up your practical in the usual manner, pasting the printed Excel spreadsheets under the RESULTS section.

7 Vibrating String

NOTE:

The ‘deliverable’ for this practical is a full write-up to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on performing a Type B uncertainty analysis, propagating uncertainties and comparing measurements.

7.1 Aim

The aim of this practical is to generate standing transverse waves in a stretched string, and to use these waves to measure their velocity. In carrying out this exercise, we hope to give students experience with Type B uncertainty evaluations, uncertainty propagation and comparison of measurements.

7.2 Introduction

Waves are generated in a string by a vibrator fed from a function generator, as shown in Figure 7-1.

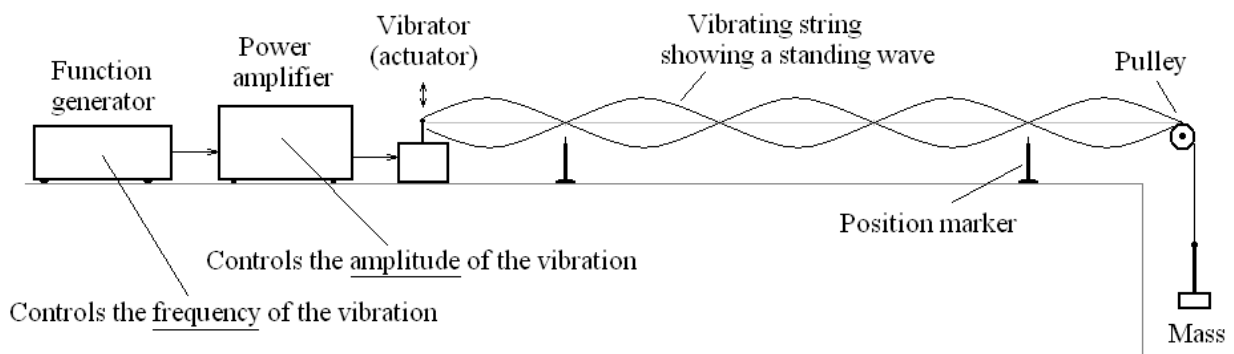


Figure 7-1 Apparatus used to generate standing waves.

The frequency, f , of the waves, their wavelength, λ , and velocity, v , are related by the equation:

$$v = f \lambda .$$

Since the string is effectively fixed at the “pulley end”, the travelling waves propagating along the string are reflected at this end and the reflected waves interfere with the forward travelling waves. At certain frequencies, standing waves are produced and several nodes will be clearly

visible. Since the distance between adjacent nodes is equal to half a wavelength (i.e. $\lambda/2$), it is possible to determine the wavelength of the waves under these conditions. A plot of f vs $1/\lambda$ should yield a straight-line graph with slope v through the origin.

The velocity of the transverse waves is ultimately determined by the tension, T , in the string and the mass per unit length, μ , of the string viz.:

$$v = \sqrt{T/\mu}.$$

It is therefore possible to compare the measured wave velocity to that predicted by theory if the tension in the string and the mass per unit length of the string are known.

7.3 Apparatus and Method

Measure the mass of the mass piece used to tension the string. As this need not necessarily be done at the beginning of the practical, you may wish to delay this measurement until later if the queue for the scale is too long.

Connect the apparatus as in Figure 7-1 and adjust the function generator and the power amplifier to find the frequency at which the standing wave on the string has 3 or 4 nodes. (Note: Since the vibrating unit generates the waves in the string by moving up and down, the point at which the string is attached to the vibrator is not a node.)

PLEASE NOTE: The tips of vibrators are fragile. They should not be overdriven by applying too much power and, in particular, they should NEVER BE TOUCHED while undergoing vibration.

Measure the distance L between the extreme left and right-hand nodes and, hence, obtain the wavelength of the waves. Increase the frequency and repeat the measurements at other standing wave positions until at least 6 measurements have been made in the range from about 3 to 15 nodes. Tabulate all the readings and then plot a graph of f vs $1/\lambda$. From your graph, determine the velocity of the waves. For the uncertainty evaluation, consider the “extreme best-fits” to your data by eye.

In order to determine the wave velocity predicted by theory, the tension in the string and the mass per unit length of the string need to be established. Since the tension in the string is

produced by the mass piece attached to the string, measuring this mass allows the tension to be determined.

To measure the mass per unit length of the string, a length of string is supplied alongside the triple beam balance. Measure the length and mass of the string and determine its mass per unit length. Then calculate the “predicted” velocity.

You will need to pay careful attention to uncertainties: the uncertainties in the mass of the mass piece, the mass of the piece of string, and the length of the piece of string are all determined by Type B evaluations. Assume an acceleration due to gravity of $(9.80 \pm 0.02) \text{ m/s}^2$. The combined uncertainty in the predicted value for v is then determined using the technique of uncertainty propagation.

7.4 Comparison of Results

You are now in a position to compare your measured and ‘predicted’ results for v . Decide whether your measured and ‘predicted’ results agree and comment on the possible sources of any discrepancy.

8 Optics

NOTE:

*The 'deliverable' for this practical is an abridged write-up (**containing just the Results, Analysis and Conclusions**) to be handed in by 5:00 pm on the day of the practical. In this practical, the emphasis is on performing both Type A and Type B uncertainty analyses and comparing measurement results.*

8.1 Aim

The aim of this practical is to determine the focal length of a thin converging lens. In carrying out the exercise, we expect that students will consolidate the techniques of Type A and B uncertainty analyses and measurement comparison.

8.2 Introduction

Thin lenses are extensively used in scientific and medical equipment, e.g. in telescopes, microscopes and video cameras. Basic to their operation is the theory of geometric optics, which deals primarily with mirrors and thin lenses, and which you may already have covered in your lectures.

This practical relies heavily on the use of the method of parallax, described in the next section.

8.3 Apparatus and method

Begin the afternoon's practical by obtaining an approximate value for the focal length of the converging lens by using the "distant object" and "parallax" methods. Once you have a reasonable idea of the focal length of your lens, proceed to a more thorough determination using the method of "conjugate foci".

In geometrical optics we frequently need to locate and measure the position of an image, or to adjust an optical system forming an image, so that the image is located at a particular position, such as the crosswires in the eyepiece of a telescope or microscope. For example, when a pin is viewed through a lens, we may see an image of the pin which is formed at a position different from that of the pin itself. The position of the object, or pin, is easy to measure, but how can we

determine the position of its image? Additionally, in the case of a microscope or telescope, how can we ascertain that the position of the image which we observe coincides with the crosswires in the eyepiece? The method of no parallax provides a technique for achieving these objectives.

Parallax is defined as the apparent displacement of one body with respect to another when the position of the observer (not of the bodies) is changed. As an example, two pencils may be held at arm's length in line with one eye, but with one pencil a few centimetres behind the other. Hold one pencil point up, the other above and behind it with the point down. Without moving the pencils, move your head from side to side. Note how the pencils seem to move apart and together again as you move your head.

However, as you bring the more distant pencil closer to you, the relative sideways movement of the pencils decreases. Eventually, when the two pencils are exactly the same distance from your eye, moving your head does not cause a relative shift of the pencils. At this stage, we say there is "no parallax" between the pencils and we can be confident that they are the same distance from the eye. The same technique can be used to set two images (whether real or virtual) at the same distance from the eye, or, for that matter, an image and a pin, or perhaps an image and a crosswire.

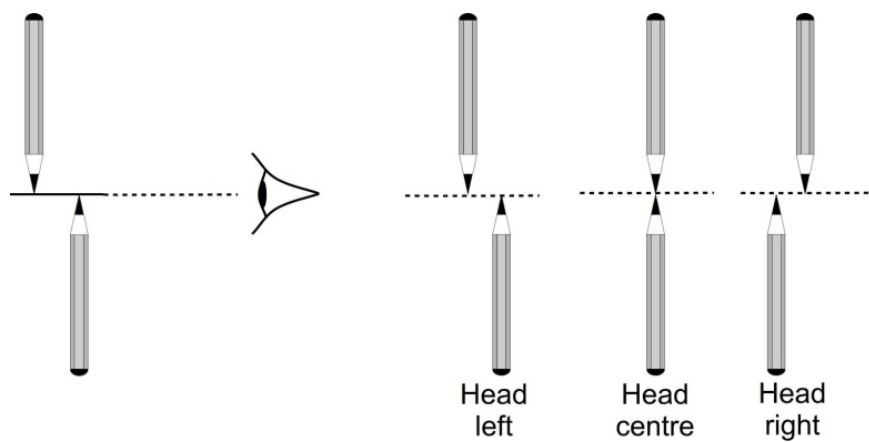


Figure 8-1 With parallax

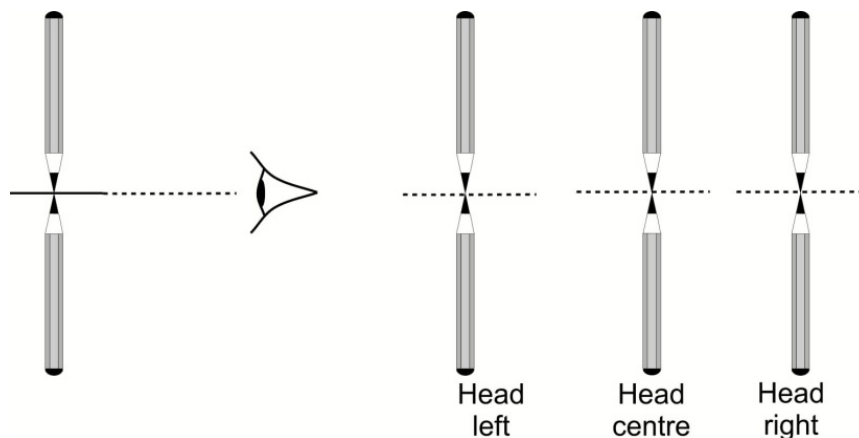


Figure 8-2 No parallax

8.3.1 Distant object method

Arrange the optical bench so that light from an illuminated object at least 10 m away (e.g. the windows at the far side of the laboratory) falls on the lens. Set up the white screen on the opposite side of the lens, adjusting its position until the image of the window is sharply focused on the screen. Since the rays arriving at the lens from the window are essentially parallel, they will form an image at the lens' focal length. The distance between the lens and the screen is thus the focal length of the lens. In order to determine the uncertainty in the focal length obtained using this method, one needs to perform a Type B analysis. Draw up an uncertainty budget, listing all major contributions to the uncertainty in the measurand (the focal length). Estimate all uncertainties and quote the result for the measurand f obtained in this way.

8.3.2 Parallax method

Remove the screen and replace it with a pin. Looking through the lens, adjust the position of the pin so that there is no parallax between the pin and the image of the window. The pin now marks the position of the image, and the distance from the lens to the pin is the focal length. As with the distant object method, perform a Type B uncertainty analysis (draw up an uncertainty budget, estimate each contribution and combine them to obtain the uncertainty for f measured in this way).

8.3.3 Method of conjugate foci

This method makes use of the thin lens formula:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i},$$

where f = lens focal length, d_o = object-to-lens distance, and d_i = image-to-lens distance.

Place the lens near the centre mark of the optical bench, and the object-pin about 40-50 cm from the lens. Looking from the opposite side of the lens, locate the inverted image of the object-pin. Now use the locating-pin to mark the position of the image, by the method of no parallax. Record the positions of the object-pin and locating-pin (image-pin). Move the object-pin a few centimetres closer to the lens, keeping the position of the lens fixed. Locate the image as before, recording your new set of readings. Each member of the group should take turns to set up the pins and read off their positions.

Repeat until you have about five or six sets of readings over a reasonable range. Then tabulate d_o , d_i , $1/d_o$, $1/d_i$ and f for each set of readings. Since you now have multiple (five or six) values for f , you can perform a Type A analysis to obtain the result of this method.

Finally compare the results obtained for the focal length from the three methods.

8.4 Exercise

To conclude this practical, complete the following exercise. Place the object-pin about 40 cm from the lens. Looking from the opposite side of the lens, locate the inverted image of the object-pin. Slowly move the object-pin towards the lens, noting what happens to the size and orientation of the image. Describe your observations and explain what gave rise to the behaviour observed.