BPhO British Physics Olympiad

BPhO EXPERIMENTAL PROJECT 2014

GRAVITATIONAL ASSIST SLINGSHOT EXPERIMENT

INTRODUCTION

Over fifty years ago space travel was solely determined by the quantity and power of a rocket's fuel propellant. However in 1961 Michael Minovitch, working at the Jet Propulsion Laboratory in the USA, realized that the velocity of a spacecraft could be substantially increased during its passage (or "flyby"), past a planet by a 'gravity assist slingshot manoeuvre'. During the flyby the energy and momentum of the system of planet and spacecraft are conserved. There is a possible range of relative velocities of the two bodies for which the planet will lose an exceedingly small fraction of its energy and the spacecraft will gain this energy, which will increase its energy and velocity appreciably.

This slingshot effect has subsequently been used extensively in space missions. In one of the earliest missions, the Voyager II mission to the outer planets which began in 1977, the spacecraft flew by Jupiter, Saturn, Uranus and Neptune. In each flyby it increased its speed appreciably as a result of the slingshot effect. It reached Neptune in 12 years, a journey that would have taken over 30 years without the gravitational assist of the slingshot effect. Most subsequent missions have made use of the slingshot effect.

For missions to the two inner planets, Mercury and Venus, it is necessary to slow down the spacecraft, which otherwise would be accelerated by the gravitational field of the Sun. In this case the slingshot effect can be applied to slow the spacecraft; the planet gaining energy from the spacecraft.

THE EXPERIMENT

The experiment is a simplified, one dimensional, version of the slingshot effect used in space missions. In the experiment a tennis ball gains energy from a football. The football represents a planet and the tennis ball represents the spacecraft.

The tennis ball sits on the top of the football. Both are released simultaneously from rest and fall together, under gravity, to the floor (see Figure 1). The football, with the tennis ball on top, will be 'reflected' from the floor. It will, on reflection, give the tennis ball a 'kick'. As a result the tennis ball will rise to a height that is appreciably greater than its initial height above the floor. The football, with the smaller velocity, rises to a height that is not very much less than the rebound height when dropped alone from the initial height.

In an ideal situation with small, perfectly elastic balls (with the top ball being much lighter than the lower ball) and perfectly elastic collisions, and the small ball will rise to a height that is nine times its initial height above the floor. This can be deduced using the laws of conservation of energy and momentum. The balls are not perfectly elastic, so their collisions will not be perfectly elastic. However the centre of the tennis ball will still rise to a height that is appreciably greater than its initial height.

In the experiment the initial height of the centre of the football, h_F , is determined before releasing the balls and the final height of the centre of the tennis ball, h_T is measured. Both are tabulated. From these results the velocity of impact of the football on the floor, v_F, (using $v_F = \sqrt{2gh_F}$) and the velocity of the tennis ball after receiving a 'kick' from the football, v_T, can be deduced.

EXPERIMENTAL DETAILS

To ensure the tennis ball sits stably on top of the football when both fall together under gravity, one should fix a rubber ring of diameter approximately 2.5 cm on top of the tennis ball with Araldite or an alternative glue or double sided sticky tape. Make sure, in the case of the sticky tape, that the tennis ball will not stick to the football when placed on the ring. An O-ring (these can be purchased from a hardware store) would be suitable (of approximate thickness 3 mm or greater). A metal ring can be used if a rubber one not available.

The two balls are released from rest. The distance they fall initially should be varied from a few centimetres to more than a metre. Measurements of h_F and h_T should be made and tabulated. For each value of h_F the measurement of h_T must be repeated several times to obtain an accurate value of h_T . These measurements can most conveniently made by videoing the tennis ball against the background of a series of metre rules, or a measuring tape laid vertically from floor to ceiling. It is preferable to perform the experiment on a solid floor, not a carpeted floor, in order to maximize the rebound energy. h_T will be limited by the height of the laboratory ceiling.

A graph of h_T against h_F is to be plotted. Calculate the 'kick' velocity of the tennis ball, v_T and the velocity of the football on impact with the floor, v_F , for all data sets .
Plot a graph of v_T against v_F.

APPARATUS

1. a football (pumped up)
2. a tennis ball
3. an O – ring, diameter approximately 2.5 cm, thickness approximately 3 mm plus Araldite or alternative glue or double sided sticky tape
4. measuring instruments e.g. metre rules/ measuring tape

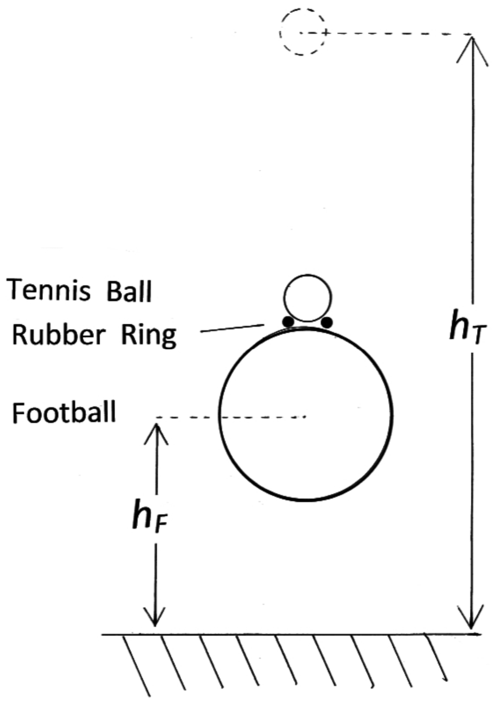

Figure 1. Arrangement of balls.

Note that the heights are measured to the centres of the balls.

Experimental Report

This report should contain:

(i) A concise description of the experimental procedure, including diagrams/photographs.
(ii) An outline of any experimental techniques used to improve accuracy or reduce uncertainty, and/or modifications to the procedure based on any trail experiments.
(iii) Precautions taken to consider safety.
(iv) Tables of measurements including the **radius** and **mass** of each ball.
(v) Errors and accuracy estimates and comments about them.
(vi) A concluding discussion of results, units and accuracy.
(vii) A photograph of the experimental arrangement.
(viii) Calculations.

Report Guidelines

You should give a full but concise description of the experimental procedure. Highlight any particular ideas you had to make the results more reliable, with results, tables, units, uncertainties, graphs, diagrams and images. This is elaborated below.

- You must include a plan of the experiment, such that a colleague could carry out the experiment from your instructions. You must also write about any additional points, the particular apparatus that you used (type of ball), precautions you took and good ideas you had about reducing the uncertainties of your measurements and what were the difficult measurements to make and why. Do not write an essay but just a short comment about each good idea.

- Describe any trial measurements you made to see if the experiment was going to work. Say what changes or adjustments or range setting you made in the light of this experience. Perhaps you needed a higher ceiling or different floor.

- You should **describe briefly in words** how you measured the heights.

- Take a **good range** of data, and **plot the graphs before you put the apparatus away**. You may find that you do not want an even spread of results, but that you need more at some particular values of h_F and rather fewer at other values of h_F. You do not have to take all of the readings in the right order. They will sort themselves out on the graph.

- Results tables should have the **original data** including any **repeated measurements**, with the **units** at the top of the column along with the **correct symbol** for the quantity. A column for the **average** can then be worked out. You might include a column with an **estimate of the uncertainty** on your average value.

- If you feel that the results are not right, then don't scribble them out or delete them; keep them and just point out what might be wrong with them or why you have no confidence in them. The purpose is to show that you have **investigated the apparatus** and given it a good try out so that you can convince the reader that you **know what you are talking about**. Things can go wrong and you need to show how you can overcome setbacks. If you delete everything that does not seem right to you, the reader might see a nice final table of results, but they do not know how much investigative effort you have put in to get that set of results. The reader might indeed wonder whether they are that good. Do **not** write an essay, just a few bullet point comments.

- Graphs should have labelled axes, units on the axes, with the plotted data taking up a significant proportion of the graph paper area, some gridlines if done in Excel so that the reader can get values off the graph, a scatter graph with a line of best fit (trendline in Excel) – definitely do not "join the points". Display the equation for the trendline on the graph. **Comment on the graph** i.e. look at it and state what you can see about the shape of the graph, the scattering of the points, does it go anywhere near the origin, is it a straight line or a curve (or is it hard to tell), is the data close enough to the line of best fit to agree with the uncertainties you wrote down in your table of results?

- The **conclusion** comes from the table of results and your graph. What **trends** are shown, or what **general comments** can you make to **summarise** your results. You should also make at least a **comment** about whether you yourself think that the results are reliable or not, and why.

Good Luck with the experiment!