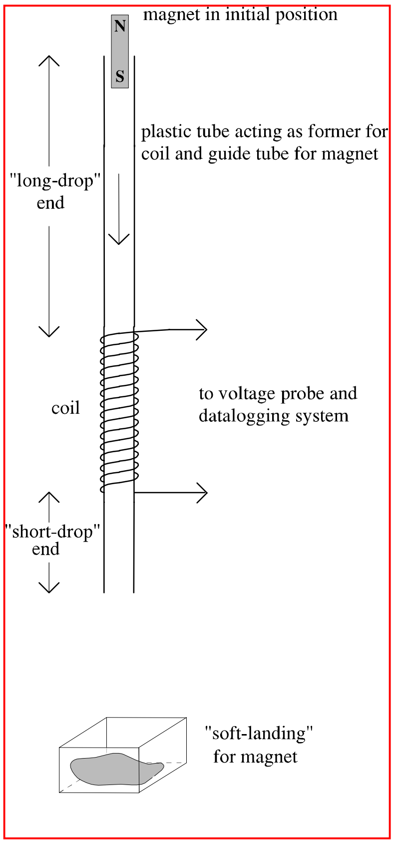
Practical Activity on Induced Voltage

Introduction



In this experiment you will investigate the variation of induced emf in a coil as a magnet is dropped through the coil. The passage of the magnet through the coil takes place in about 100 ms and hence to investigate what is happening in detail the induced emf is datalogged at intervals no larger than 1 ms. Looking at the trace of emf versus time and investigating how it varies with changing circumstances gives a lot of insight into the process of induced emf.

School pupils first meet the concept of "induced voltage" in the *Energy Matters* unit of Standard Grade Physics or in the *Electromagnetism* section of Intermediate 2 Physics. By moving a bar magnet into or out of a coil it is easy to obtain momentary "kicks" on a galvanometer. With a sufficiently sensitive galvanometer it is also possible to observe the induced voltage caused by moving a single wire across a magnetic field. In either case, however, the inertia of the galvanometer suspension is too great to follow the detailed time-variation of the induced voltage. In our activity the data-logger records the complete voltage-time variation as a bar magnet falls through a long coil, i.e. as it enters at one end, passes inside, and emerges at the other end.

The next two-and-a-half pages give the background theory that explains what is going on. It is here mostly for reference to help with the interpretation of the results. The description of the experimental details begins on page 4.

Background Concepts and Theory

1. If a **uniform** magnetic field of magnetic induction **B** passes **normally** through an area *A* then the flux ϕ of **B** through the area is defined as

$$\phi = BA \quad . \tag{3}$$

The unit of ϕ is therefore **tesla-metre**^{2} (**T m**^{2}). This is equivalent to **volt-second** (**V s**), as can be seen at a glance from equation (4) below. The unit of ϕ is also named the **weber** (**Wb**).

2. According to Maxwell's third equation (equivalent to Faraday's law of induction), if the flux of **B** through an area A is changing, then an electric field exists round the perimeter of the area A. If there is a wire round the perimeter, then the electric field, which exists whether the wire is there or not, will drive a current round the wire.

The usual way to drive a current round a wire is to use a battery to create the **E** field in the wire. If the battery voltage is V and the wire has resistance R, then the current I in the wire is given by I = V/R. The electric field in the wire is the gradient of the potential along the wire. Taking the zero of potential at the negative terminal of the battery, the potential falls from V at the positive terminal to 0 in the length, ℓ, of the wire. Hence E = V/ℓ. So I = Eℓ/R. All this is shown in Fig. 1(a) below.

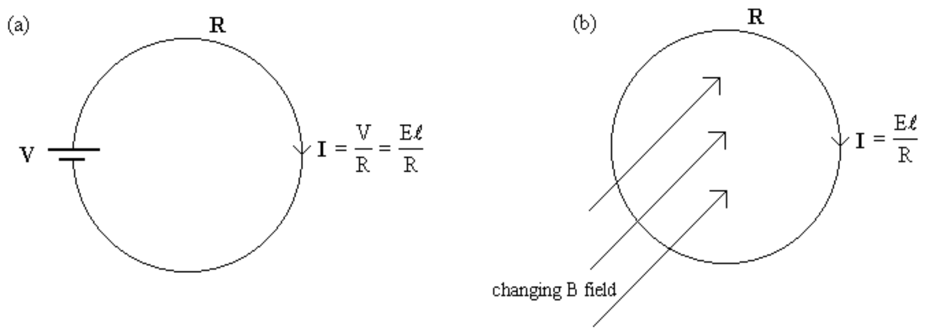


Fig. 1

If the same current is ***induced*** in the same loop [Fig. 1(b)] by a changing magnetic field, then the electric field in the wire must be the same. So the current is I = Eℓ/R, as before, but, since there is no battery, it is attributed to an ***electromotive force*** (*emf*), Eℓ. The emf is ***not*** a mechanical force; it has the dimensions of a voltage and has the same effect as the equivalent voltage source.

Faraday's great insight was to link the induced emf, ε, to the changing magnetic flux through the area bounded by the wire. The relationship is:

$$\varepsilon = E\ell = -\frac{d\phi}{dt} \quad . \tag{4}$$

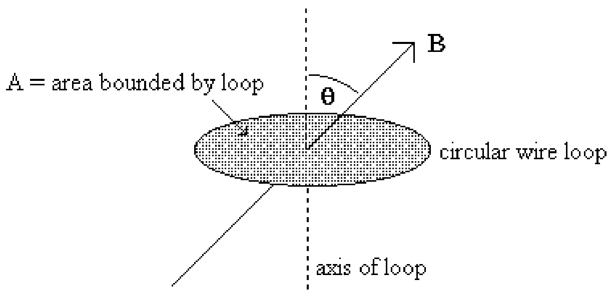
The negative sign is important. If the flux increases, the sense of the induced **E** field is to drive a current round the loop in the direction that will reduce the flux through the loop. That is, the current induced in the loop creates a magnetic field whose flux through the loop **opposes the change**.

3. If the magnetic field is **uniform** but passes **obliquely** through a single loop, the flux ϕ through the loop is determined by the component of B normal to the loop.

$$\phi = BA\cos\theta \quad . \tag{5}$$

This is illustrated in the following diagram (Fig. 2).

Fig. 2



θ is the angle between the magnetic field and the **normal** to the area defined by the loop.

If the loop is a flat coil of N turns, then the total flux through the coil is N times the flux for a single turn, namely

$$\phi = NBA\cos\theta \quad . \tag{6}$$

If the coil is extended and the field is non-uniform, then the total flux has to be calculated by adding up the flux through each turn.

Now think about a magnet dropping through a coil. We can see from Fig. 3 below that the flux through each turn involves an integration, over the coil cross-section, of a **B** field that varies in strength and angle over the area. Furthermore, the flux through an individual turn diminishes as the magnet gets further away from the turn.

Note that the lines of **B**, as always, form closed loops. The **B** field is not continuous across the interface between a material of the magnet and the surrounding air; only the component normal to the surface is continuous. This accounts for the 'kinks' in **B** shown at the surface of the magnet.

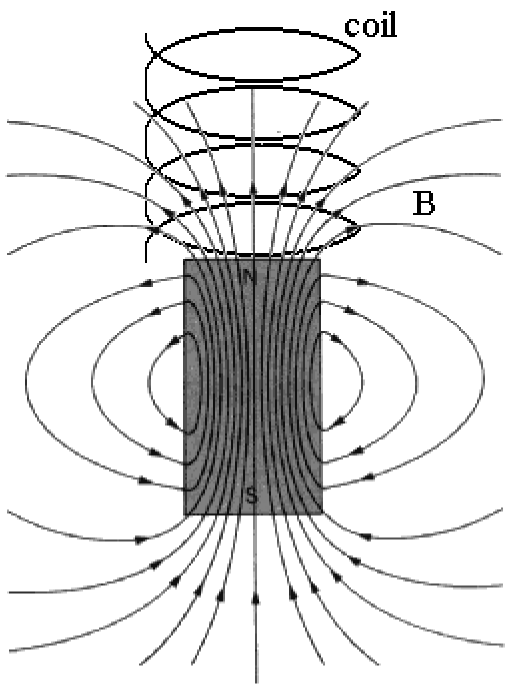


Fig. 3

At this point it becomes simpler to make experiments to see what happens!

Relevance of the above theory to the Practical Activity

It should be clear that the apparently simple situation of a magnet dropping through a coil is in fact complex. Some idea of the complexity may be judged from the following diagrams [Fig 4], which show various stages of the drop.

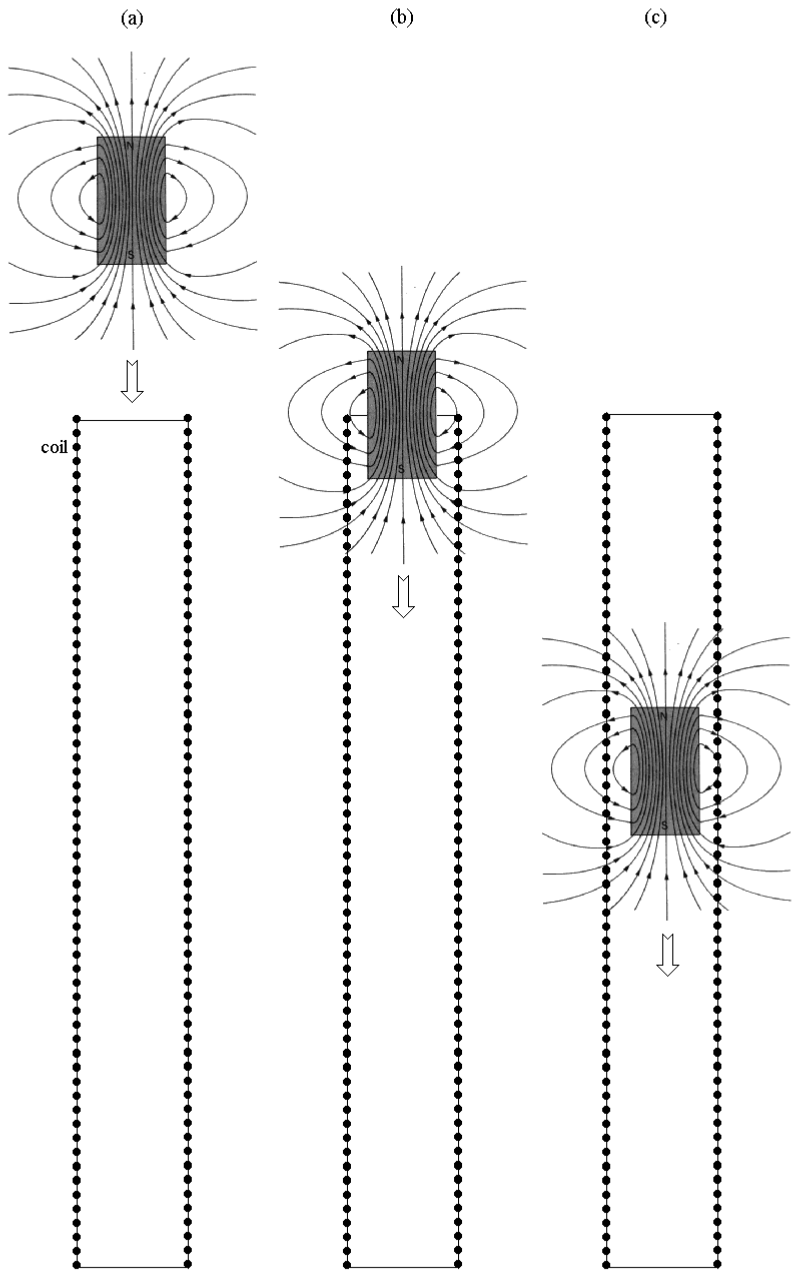


Fig. 4

Fig. 4 gives us some insight into the total flux through the many turns of the long coil and the rate of change of this flux as the magnet falls.

A complete theoretical analysis of the emf created by the falling magnet involves:

(a) calculation of the total flux through the coil at an arbitrary instant;

(b) calculation of the rate of change of this quantity.

Let's datalog it instead! You can see, though, that the conspicuous changes are going to take place when the magnet enters the coil and when it leaves it.

Experiment Aim

To investigate the variation with time of the emf induced in a coil as a bar magnet falls through it.

Set-up

The following are provided:

3 coils

(a) 100 turns in single layer; 100 mm length;
(b) 200 turns in single layer; 200 mm length;
(c) 200 turns in double layer; 100 mm length.

2 bar magnets

(a) *Rectangular cross-section*
Dimensions 50 x 15 x 10 mm
Flux-density at centre of faces ~ 0.3.T .

(b) *Circular cross-section*

Dimensions 20 mm (length) x 6 mm (diam)

Flux-density at centre of faces ~ 0.4T

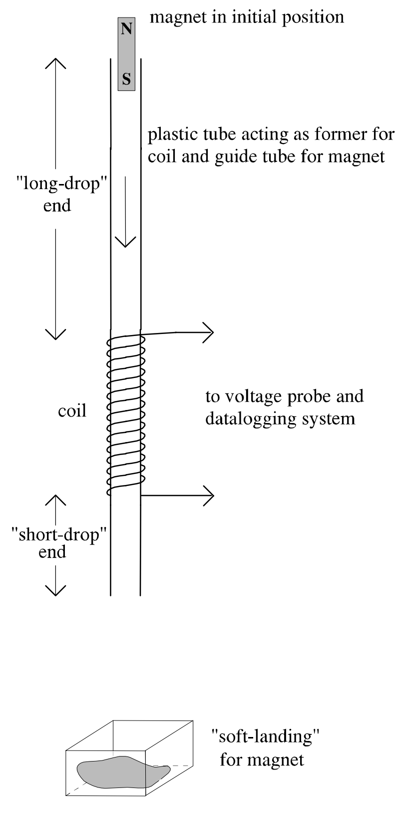


Fig.5

There is a choice of 4 datalogging systems:

(a) Pasco Science Workshop 500 Interface using Data Studio software

(b) Vernier Datalogging: LabPro Interface with TI-83 Plus Graphing Calculator

(c) LabView PC data-logger and analysis package

(d) Alba interface and logger with Alba software.

Preliminary sampling conditions have been selected as follows:

Data-logger	Sampling Data		Triggering Conditions	
	Frequency (Hz)	Total Time (s)	Threshold (V)	Nature of Change
Pasco	1000	0.12	0.003	Rising Voltage
Vernier	2000	0.12	0.005	Rising Voltage
LabView	10,000	0.4	0.0005	Either ↑ or ↓
Alba	8333	0.12	0.02 (or 0.03)	Rising voltage

Experimental Procedure

1. Click or select START, GO, etc. (depending on data-logger used).

2. Drop the magnet through the tube, starting it at the top of the tube.

3. Inspect the trace and measure:

   (i) the maximum induced emf on approach;
   (ii) the maximum induced emf on recession;
   (iii) the time interval between (i) and (ii);
   (iv) the area of the approach peak (use the area function of the data-logger);
   (v) the area of the recession peak.

Can you relate the trace to the law of induction? Look through the questions below and using the repetitions 4, 5 and 6 suggested here build up a set of trial drops that enable you to answer these questions. You can save traces to the floppy disk provided and print them on the printer in the lab. This experiment if open ended. You will almost certainly think of variations that your pupils could investigate in some detail if they tackled something similar.

4. Repeat for the other magnet

5. Repeat for other coils.

6. Repeat for different dropping heights (invert coil tubes and/or use extension tubes). Consult a demonstrator if necessary.

Questions

1. Interpret the features in your display.

2. Why are there two peaks of opposite sign?

3. Why is only one peak sometimes obtained? (This is an artefact of the sensing arrangement, not a fundamental issue.)

4. Why is the maximum induced emf for approach less than that for recession?

5. Give a qualitative explanation of the difference in the traces for the two magnets.

6. Explain the difference in the results obtained when using the three different coils with the same magnet.

7. What is the significance of the area measurements?

8. Explain the change in the display as the dropping height of the magnet is increased.

9. List any ideas that occur to you for using this experiment as the basis of an Advanced Higher Investigation.

10 In Figs. 3 and 4, why have the lines of **B** been shown inside the magnet as well as outside?

11 How would you adapt the experiment to obtain voltage-time graphs for the pupil experiment mentioned in the **Introduction** that involves moving the bar magnet into and out of the coil?

12 (a) Calculate the free-fall time for a magnet to drop from one end of a coil to the other.
(b) How does this compare with the time interval between the 'approach peak' and the 'recession peak'?
(c) Consider possible reasons for the discrepancy between (a) and (b).

13. Let t_A = instant at which approach peak occurs.
t_B = instant at which recession peak occurs.
$\Delta t_{AB} = t_B - t_A$.

(i) Compare the values of t_A and Δt_{AB} for the following pairs of situations:
  (a) Constant strength of magnet; constant drop height; coils of different number of turns per unit length.
  (b) Constant strength of magnet; constant number of turns and length of coil; different drop heights.
  (c) Constant strength of magnet; constant drop height; coils of different lengths but having the same number of turns per unit length.

(ii) Account for your findings in (a), (b) and (c).

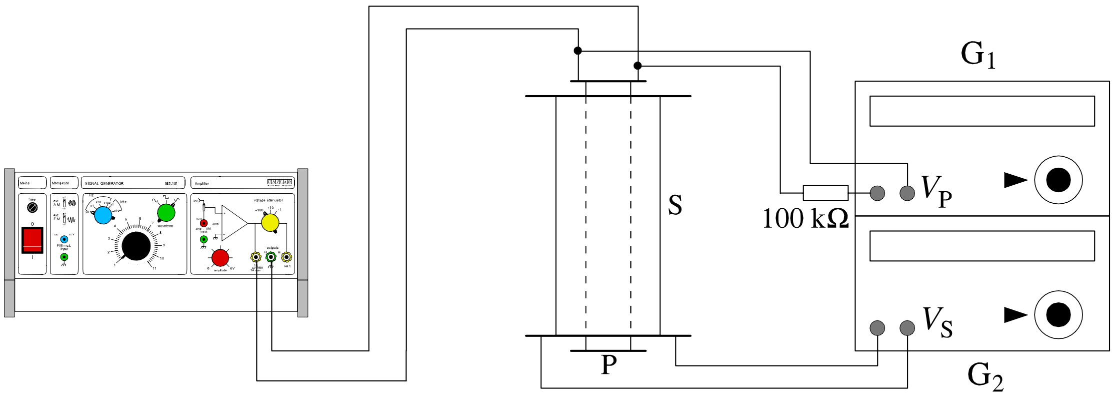
14. Is there a systematic discrepancy between the areas of the two peaks? If so, account for this.

15. What energy conversions are involved during the dropping of the magnet? Can this be quantified experimentally?

Space for notes and results

Demonstration of the relationship $\varepsilon = -\dfrac{d\phi}{dt}$

This is a separate demonstration for you to try. The arrangement is indicated in Fig. 6 and is largely self-explanatory.



Unilab signal generator
set to : triangular waveform
output voltage 1 V
output frequency 0.1 Hz

P primary coil (few turns: R = 1.1 Ω)
S secondary coil (many turns: R = 94.5 Ω)
G_1 WPA galvanometer K107; range X .03
G_2 WPA galvanometer KN90; range X 1

Fig.6

Warning: Please do not use the square wave output of the signal generator!

A low frequency, triangular output from the signal generator applies a voltage V_p to the primary coil P. Provided the frequency is low enough the current ramps up and down at a uniform rate.

Since $\phi_P \propto I_P$ and, in this case, $I_P \propto V_P$, it follows that the magnetic flux in the primary coil increases at a uniform rate, then decreases at a uniform rate, and continues to alternate in this way.

Since $\varepsilon_S = -\dfrac{d\phi_P}{dt}$ at any instant, the emf ε_S induced in the secondary coil has the following features:

- ε_S = constant and negative whilst ϕ_P is increasing at a uniform rate.
- ε_S = constant and positive whilst ϕ_P is decreasing at a uniform rate.
- ε_S changes sign when ϕ_P changes from increasing to decreasing and also from decreasing to increasing.

Note the sign of ϕ_P itself is irrelevant! It is the sign of $\dfrac{d\phi_P}{dt}$ that is important. [Compare velocity and acceleration in this respect]

The voltage-time variations for ϕ_P and ε_S are as follows (Fig. 7):

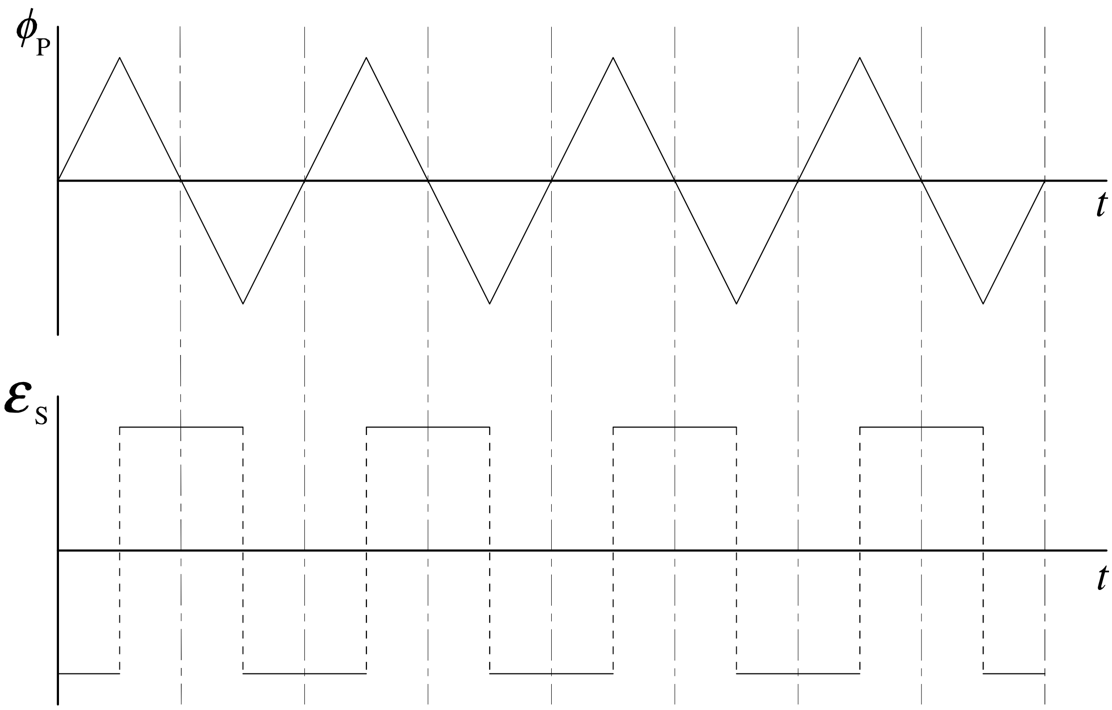


Fig.7

Questions

1. What would you expect to be the effect on the voltage-time graphs of the following:

    a. Increasing the supply frequency?
    b. Decreasing the supply voltage?
    c. Changing from triangular output to sinusoidal output in the signal generator?
    d. Introducing soft-iron into the coil system?

    Warning: Please do not use the square wave output!

2. Estimate the mutual inductance of the air-cored coil system.

Additional Data

Instrument sensitivities and resistances are approximately:

K107:	Primary voltage	76 mV cm^{-1}	Resistance 2.4 kΩ (+100 kΩ in series).
KN90:	Secondary current	0.56 μA cm^{-1}	Resistance 13 Ω.
	Secondary emf*	6.0 μV cm^{-1}	

* This takes into account the resistances of both the meter (13 Ω) and the secondary coil (94.5 Ω).

The resistance of the primary coil is 1.1 Ω.

Finally, every physics "demo" has its gremlins. In this case it is the output of the signal generator. At the very low frequencies used in the triangular output, there can be something like a "glitch" in the uniformity of the ramp. This has a corresponding effect on the emf induced in the secondary coil. Know about this in advance and make a virtue of necessity!

Further space for notes