A datalogger demonstration of electromagnetic induction with a falling, oscillating and swinging magnet

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A datalogger demonstration of electromagnetic induction with a falling, oscillating and swinging magnet

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Abstract
We investigate the electromagnetic induction phenomenon for a *falling*, *oscillating* and *swinging* magnet and a coil, with the help of a datalogger. For each situation, we discuss the salient aspects of the phenomenon, with the aid of diagrams, and relate the motion of the magnet to its mathematical and graphical representations. Using various representation modes to guide student thinking on how the variation of the magnetic flux can be used to predict the induced electromotive force should help students develop a deeper and more coherent conceptual understanding of the phenomenon.

Introduction

Electromagnetic induction is notoriously difficult for most students. Unlike mechanics, where many situations involve familiar macroscopic objects, more abstract concepts such as field, flux [1] and the mathematical reasoning that is needed in considering rates of change [2] are often daunting for students. In addition to the lack of a firm understanding and intuitive feel for the phenomenon, the associated graphical representations (e.g. Φ–t graph and V–t graph) are also not easily grasped by students.

The datalogger allows the study of fast changing phenomena and is an effective tool for demonstrating the laws of electromagnetic induction—namely, Faraday's law and Lenz's law. The ability to capture real-time graphs offers the important benefit for students to better visualize the associated phenomena and develop a deeper understanding of it through subsequent analysis. We used a PASCO Science Workshop datalogger system [3] for our demonstrations. The probes used included a voltage sensor to capture the induced emf and a force sensor to monitor the motion of the magnet. We will be describing and discussing, in turn, how we used the datalogger to investigate the phenomenon of electromagnetic induction in different situations: a magnet *falling* through a coil, a magnet *oscillating* in a coil and a magnet *swinging* over a coil (see figure 1).

Magnet falling through a coil

The demonstration of a magnet falling through a coil and its experimental setup are well known, and has been described elsewhere [4–6]. Here, we focus on the analysis and highlight several noteworthy features of the obtained V–t graph (see figure 2) that are associated with the electromagnetic induction phenomenon in this

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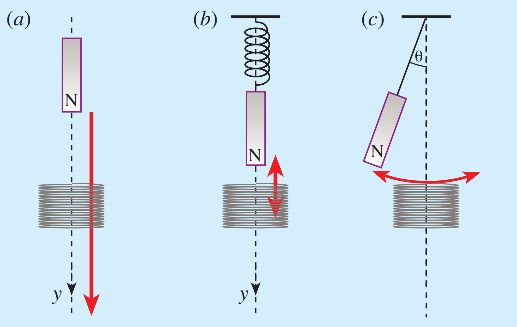

Figure 1. Setup of apparatus to demonstrate electromagnetic induction: (*a*) magnet falling through a coil, (*b*) oscillating magnet in a coil and (*c*) swinging magnet over a coil.

context. For our demonstration, the length of magnet used was about twice the length of the coil and was dropped from a height of about 30 cm from the top end of the coil.

For our setup, we can take the magnetic flux linking the coil when the magnet is high up away from the coil and way below it to be nearly zero. Hence, the net change in flux linkage is also zero. This fact is confirmed by our experimental results which indicate that the area bounded for the top part of the V–t graph (i.e. the change in flux linkage $\int V\,\mathrm{d}t$) is numerically equal to the area bounded by the bottom part of the graph. The area bounded by the graph can be easily obtained using the software, as shown in figure 2.

There is a moment in time when the induced voltage is zero. But where exactly is the position of the magnet at this time? If we were to imagine how the flux linking the coil changes along the coil axis, it would not be difficult to intuitively see that the maximum flux linkage occurs at the position where the centre of gravity of the magnet is exactly midway along the length of the coil. The flux linkage at positions just before and just after this point will be less than the maximum value (as can be seen by the Φ–t graph in figure 2). Hence the turning point on the Φ–t graph will correspond to the zero of the V–t graph since $V = -\mathrm{d}\Phi/\mathrm{d}t$.

Conceivably, if we had used a coil that was longer than the magnet, the time interval for which the induced emf remains zero would have been longer. This corresponds to the situation where the whole magnet remains well within the coil, with the magnetic flux being the maximum but remaining unchanged.

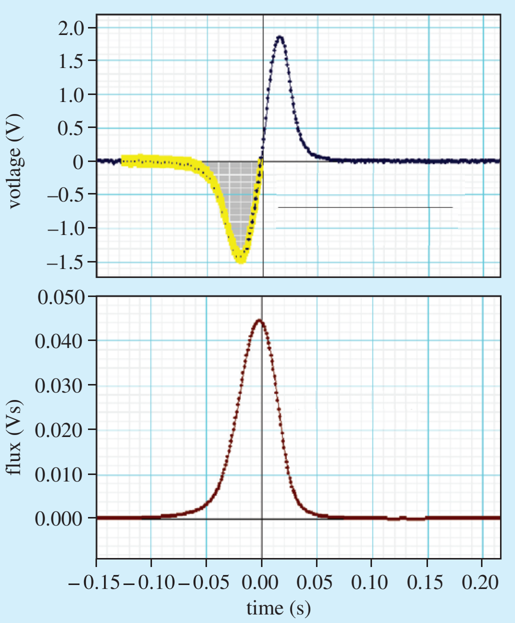

Figure 2. Graphs of induced emf and magnetic flux for a magnet falling through the coil. The flux linkage is obtained experimentally by integrating the V–t graph with time. That is, $\Phi(t) = -V(t)\mathrm{d}t$, where $\Phi(0) = 0$.

Notice next that the signs of the induced emf are opposite. This is essentially Lenz's law at play. The flux through the coil increases as the bottom end of the magnet (i.e. the north pole) approaches the top end of the coil, and reaches a maximum when the magnet is exactly midway in the coil. By Lenz's law, the induced emf will produce an upward flux that will seek to oppose the increasing magnetic flux of the magnet through the coil. Once the magnet falls past the centre of the coil, the flux through the coil starts to decrease. To reinforce the decreasing flux of the magnet through the coil, a downward flux is now induced, thereby flipping the polarity of the induced emf. Indeed, our experimental result gives a Φ–t graph (see figure 2) that is consistent with our preceding discussion. Notice also that the flux drops more sharply for the second half of the motion due to the accelerated motion of the magnet. Correspondingly, the second peak of the V–t graph (see figure 2) is greater in magnitude compared to the first and the time interval for the magnet's motion for the second part is smaller compared to the first.

It is not uncommon for students to explain the flipping of the signs of the induced emf by considering the polarity induced at each end of the coil. We feel, however, that explaining this by considering the flux instead, is accessible to students at A-level and provides them with a more intuitive and coherent understanding of electromagnetic induction.

Oscillating magnet in a coil

A common A-level examination question relates how a suspended bar magnet on a helical spring induces an emf across the ends of a coil when one end of the bar magnet is allowed to oscillate inside the coil. Students are often asked to predict how the graph of the induced emf might vary with time. From our experience, most students typically predict the induced emf to vary sinusoidally. However, a good number may not be able to pinpoint when the peak of the induced emf actually takes place (i.e. whether when the magnet is nearer the equilibrium position or nearer the positions of maximum displacement). This demonstration is an effective way to help students visualize how the induced emf actually varies in such a situation.

The force sensor was set at zero when the magnet was at its equilibrium position, and it reads positive when the spring was under compression relative to its state at equilibrium position. A sampling rate of 100 Hz was used. One end of the magnet was set to oscillate steadily within the coil and the readings taken using the datalogger. Figure 3 shows the V–t graph, F–t graph and Φ–t graph aligned on the same time axis. Let us first highlight some macro-features of the graphs.

Notice firstly that the signs of the induced emf are opposite. This is not surprising and can be easily and similarly explained using Lenz's law as in the previous case of the falling magnet. Secondly, the induced voltage at the top (e.g. positions 1 and 7) and bottom ends (e.g. position 4) of the oscillation is zero. At these positions, the speed of the magnet is momentarily zero. Hence there is no change in flux linkage at this instant and the induced emf is zero[1]. There is little damping so we can take the motion of the oscillating magnet as being nearly simple harmonic, and this is reflected by the F–t graph which is fairly sinusoidal.

We now turn our attention to the V–t graph which is clearly not quite sinusoidal. In fact the peaks of the induced voltage (positions 3 and 5) occur slightly off the equilibrium positions for the oscillating magnet (positions 2 and 6). This may seem a little odd at first thought since one might expect the induced voltage to be greatest when the speed of the oscillating object is maximum, according to Faraday's law.

Let us now examine this apparent anomaly more closely. From our experimental results, it can be seen that on the oscillating magnet's way down (position 3), the induced voltage peaks at a time slightly after the oscillating magnet passes the equilibrium position. While on its way up (position 5), the induced voltage peaks at a time slightly before it passes the equilibrium position. The opposite signs for the peaks are consistent with Lenz's law. So although the speed of the magnet is greatest at the equilibrium position, the change in flux linkage at the equilibrium position is not as big as that of the position slightly off-centre towards the bottom of the equilibrium position.

Why might this be so? Let us consider intuitively how the flux linkage might change as the magnet moves from the highest point to the lowest point of oscillation. Clearly, the flux linkage has the lowest value furthest from the coil and reaches a maximum value when the magnet is lowest within the coil. Since the magnetic field strength at the poles of the magnet falls non-linearly with distance, the magnetic flux linkage at the equilibrium position must take a value closer to zero (the lowest value) than from the peak value. Since the magnet travels in equal time intervals to and from the amplitude position and the equilibrium position, we are able to first sketch the Φ–t graph and then obtain the V–t graph by simply considering how the gradient changes on the Φ–t graph ($V = -\mathrm{d}\Phi/\mathrm{d}t$). Indeed, our experimental result gives a Φ–t graph that is consistent with our preceding discussion.

Hence knowing just the speed of the magnet will not enable us to determine the value of the induced emf. We also need to know the distribution of the total magnetic flux linkage

[1] At the positions of maximum displacement, consideration of the flux distribution is irrelevant since the change in flux is zero when the speed is momentarily zero (assuming, of course, that the magnetic field strength of the magnet remains fixed in time, and with no other external sources of magnetic field). The flux distribution becomes an important factor at other instances when the speed is non-zero, as will be discussed in the next section involving the swinging magnet.

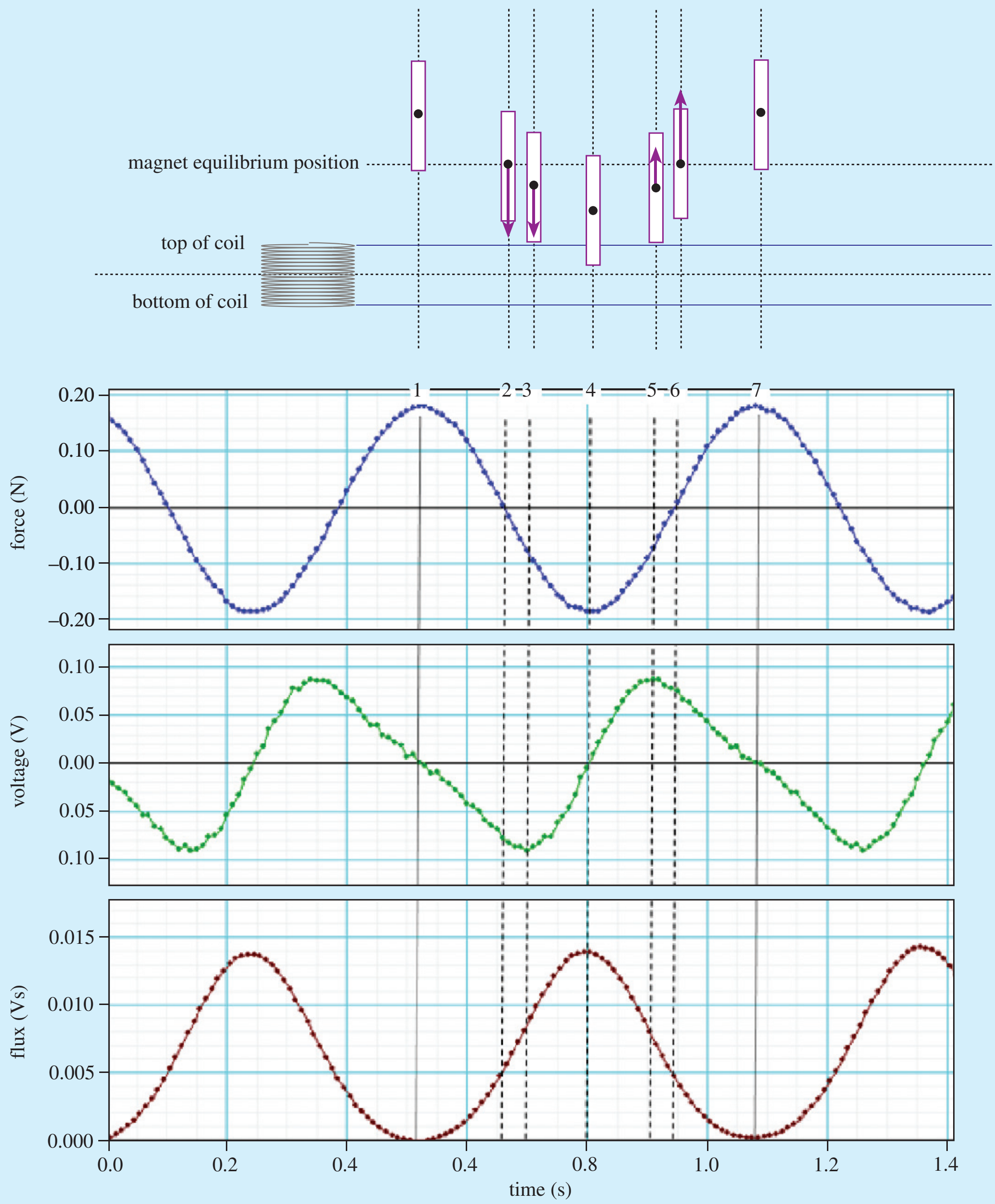

Figure 3. Graphs of force, induced emf and magnetic flux for an oscillating magnet within the coil. A diagram showing relative positions of the magnet and coil, and also the velocity vectors at points 1–7, is given above the graphs.

along the coil axis. Indeed, it is the rate at which the flux linkage changes in time that determines the value of the induced emf ($V = -\mathrm{d}\Phi/\mathrm{d}t$). Mathematically, we can write $\mathrm{d}\Phi/\mathrm{d}t$ as $(\mathrm{d}\Phi/\mathrm{d}y)\cdot(\mathrm{d}y/\mathrm{d}t)$, where y labels the position of the centre of gravity of the magnet along the axis of the coil and $\Phi(y)$ is the flux linkage when the centre of gravity of the magnet is at the position y. It is worth highlighting that the flux linkage $\Phi(y)$ is not the flux linkage at point y (which is meaningless) but the total flux linking the whole coil when the centre of gravity of the magnet is at point y.

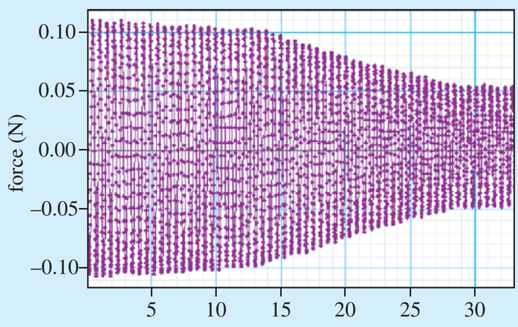

Figure 4. The effect of damping due to the induced current on the oscillating magnet in the coil.

The other interesting phenomenon that can be demonstrated is damping due to the flow of induced current when the terminals across the induced emf form a closed circuit. Figure 4 shows the force sensor reading of the oscillating magnet with time. It can be seen that heavy damping sets in at about $t = 13$ s when the terminals across the voltage sensors were shorted. When the short circuit was removed at about $t = 28$ s, the damping became appreciably less as before. This phenomenon of damping due to the induced current is consistent with the principle of the conservation of energy where the electrical energy produced in the circuit is at the expense of the mechanical energy of the oscillating spring–magnet system.

Swinging magnet over a coil

Another interesting situation is to study the induced emf caused by a magnet swinging just over a coil [7]. One end of a string was used to secure the top end of the magnet and the other end of the string was attached to the force sensor. The force sensor was set at zero when the string–magnet system (of length 46 cm) was hanging stationary at equilibrium, with the north pole of the magnet just above the coil axis. The magnet was allowed to swing freely without any obstruction, and with the string remaining taut throughout the motion. Figure 5 shows the V–t graph, F–t graph and Φ–t graph aligned on the same time axis.

For a swinging magnet, the tension in the string is greatest at the bottom of the circular arc since the speed of swing is maximum and the weight of the magnet points directly opposite to the tension in the string. Hence based on the F–t graph, positions 1 and 5 corresponds to the instant when the magnet is swinging at the lowest point just above the coil. Remember that the force sensor was tared at zero when the magnet was hanging stationary just above the coil so that there is an additional force equal to the mv_0^2/r registered by the force sensor when the magnet is in a swinging motion. Notice also that the flux linkage when the magnet is directly above the coil (positions 1 and 5) is the greatest as seen by the Φ–t graph.

Looking at the V–t graph, we see the usual flip in signs of the induced emf, which can be explained by Lenz's law. The induced emf for most parts of the time when the magnet is swinging outside the coil (between positions 2 to 4) is zero since the flux linkage is also zero (hence no change in flux linkage). However, unlike the case of the *oscillating* magnet where the induced emf is momentarily zero when the magnet is at its amplitude position of oscillation (i.e. when the speed is zero), the induced emf for the *swinging* magnet is actually momentarily zero at positions 1 and 5, even though the speed is maximum at these points! How can we explain this apparent contradiction?

If we were to imagine how the flux linking the coil changes at various positions of the swinging motion, we can intuitively picture the flux linkage to be zero at the extreme positions away from the coil and a maximum when the magnet is just directly above the coil. Here again, the turning point on the Φ–t graph will correspond to the zero of the V–t graph since $V = -\mathrm{d}\Phi/\mathrm{d}t$. Mathematically, we can write $\mathrm{d}\Phi/\mathrm{d}t$ as $(\mathrm{d}\Phi/\mathrm{d}\theta)\cdot(\mathrm{d}\theta/\mathrm{d}t)$, where θ labels the angle displaced with reference to the coil axis and $\Phi(\theta)$ is the flux linkage when the magnet is displaced at an angle θ. Interestingly, the value of $\mathrm{d}\Phi/\mathrm{d}t$ where the speed is greatest (i.e. at $\theta = 0°$), is here zero because $\mathrm{d}\Phi/\mathrm{d}\theta$ is zero (i.e. $0 = 0 \cdot \mathrm{d}\theta/\mathrm{d}t$). Whereas for the case of the oscillating magnet, the value of $\mathrm{d}\Phi/\mathrm{d}t$, when the speed is zero, is zero because $\mathrm{d}y/\mathrm{d}t$ is zero (i.e. $0 = \mathrm{d}\Phi/\mathrm{d}y \cdot 0$)

Our experience with students indicates that they may superficially correlate the size of the induced emf to how fast the magnet is moving, without consideration of the distribution of flux linkage in space. One possible source of this misconception is the traditional way in which

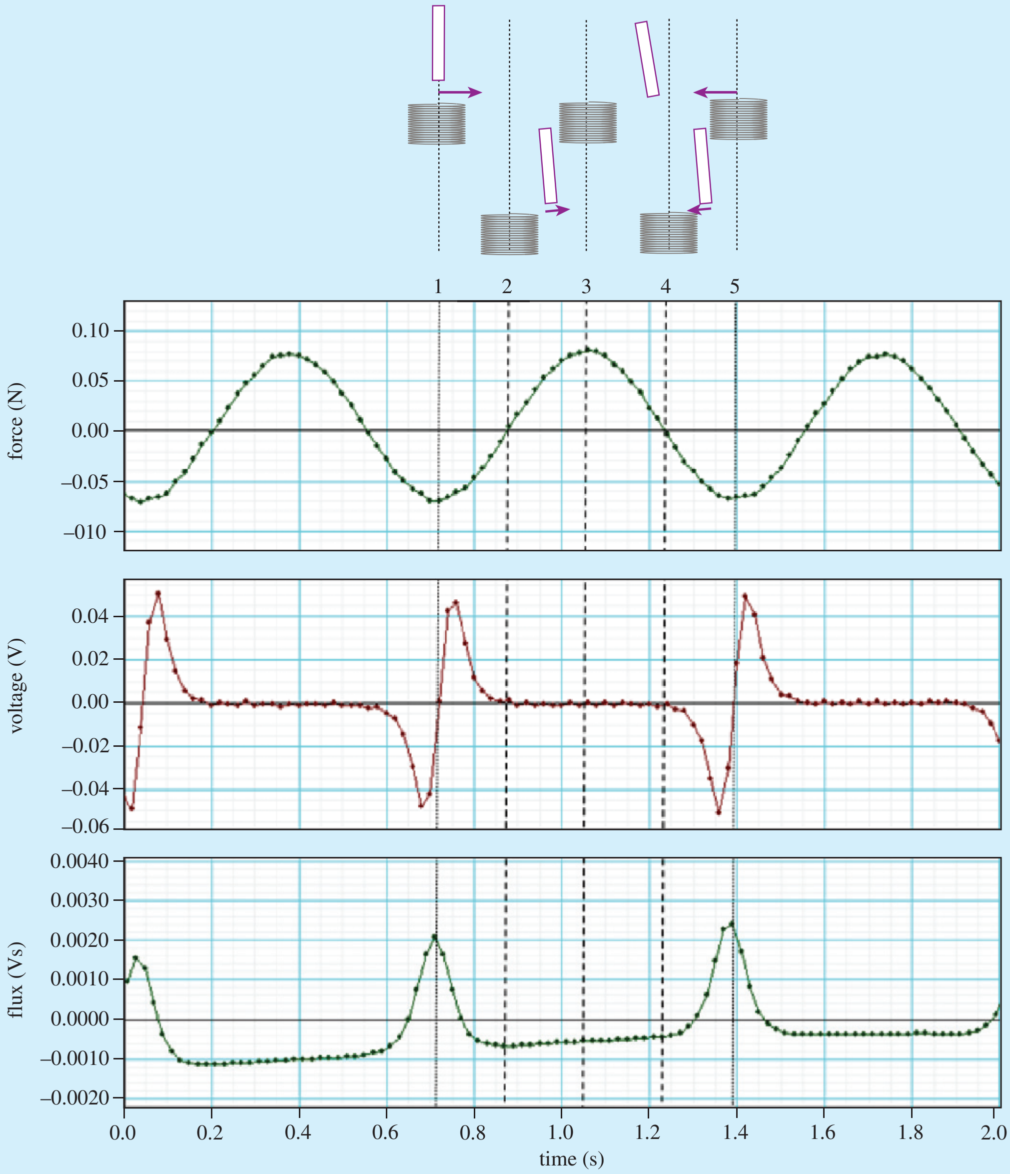

Figure 5. Graphs of force, induced emf and magnetic flux for a swinging magnet passing just above the coil. Note that the flux curve has a small upward trend due to a small offset in the voltage curve.

students are introduced to this topic, where they are shown how one end of a bar magnet moving in and out of a solenoid induces an emf. Since students observe that the galvanometer gives a larger momentary deflection when the magnet moves in and out at a greater speed, they may think the size of the induced emf is dependent solely on the magnet's speed in every context. This underlines the importance of the need to expose students to a variety of situations in helping them understand and apply a particular key concept in physics. The case of a fast moving coil cutting across a region of magnetic field, but which induces zero emf, will be a good example to present to students.

The other interesting phenomenon that can be demonstrated is the large increase in induced emf when we add an iron core inside the coil. It can

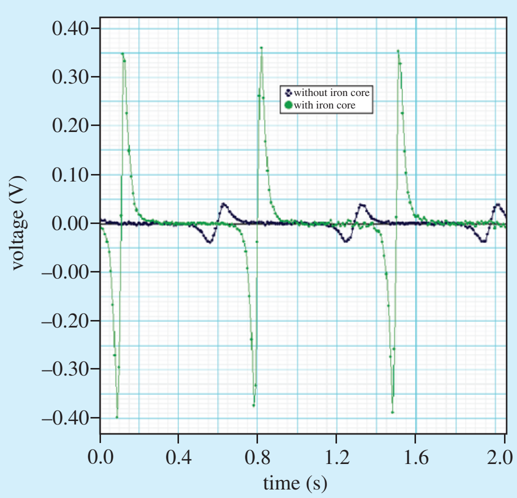

Figure 6. Graphs of induced emf for a swinging magnet with and without an iron core.

be seen from figure 6 that more than a six-fold increase in the peak value of the induced emf is obtained with the iron core inside the coil.

The increase in the induced emf is due to the increased permeability of the core in the coil. The iron core not only concentrates the field lines of the magnet but also induces additional field lines within itself. The increased change in flux linkage for nearly the same time interval therefore results in an increase in induced emf. In addition to the above-mentioned ($\mathrm{d}\Phi/\mathrm{d}\theta$) effect, there is also a ($\mathrm{d}\theta/\mathrm{d}t$) effect. As the magnet approaches the core, the attraction between the magnet and the core increases the speed, whereas as it leaves, the attraction between the magnet and the core decreases the speed of the magnet. Therefore the induced voltage during the approach is slightly higher than the induced voltage as the magnet retreats. This second effect can be seen in figure 6 where the negative spikes (∼0.40 V) have larger amplitudes than the positive spikes (∼0.35 V) with the iron core inside the coil.

Overall, the period of oscillation is not noticeably different with and without the iron core. This is because although the damping due to induced eddy currents in the iron core causes the speed to decrease, the amplitude decreases as well. However, because simple harmonic motion is isochronic, the period remains at 1.4 s, as can be seen from figure 6.

Conclusion

We have demonstrated how the datalogger can help focus and develop student understanding of electromagnetic induction using a *falling*, *oscillating*, and *swinging* magnet and a coil. Indeed, while technology itself is neutral, the more crucial factor is how the technology is used with appropriate pedagogies to teach the specific content. In this case, the skilful role of the teacher in focusing students' attention to salient aspects of the physical phenomenon (as have been discussed in this paper) and the mapping to various representational modes (e.g. graphical, diagrammatic, mathematical and verbal) is crucial in helping students to develop a more complete and coherent conceptual understanding of how the laws of electromagnetic induction apply in different contexts [8]. In particular, it would be useful to strengthen students' understanding of flux, and allow opportunities for them to develop an intuitive feel of how the flux changes with time, in order to predict how the induced emf might likewise vary. Students should be able to interpret the graphical results and relate them to the actual motion of the magnets with time and be able to verbally describe how the phenomenon applies in a particular context through the use of diagrams. Students should also be able to relate the mathematical formulation of the laws of electromagnetic induction ($V = -\mathrm{d}\Phi/\mathrm{d}t$) to the graphical representation for each situation. Appropriate pedagogical strategies would include teacher questioning and structuring the learning to create opportunities for meaningful interaction with the ICT resource.

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