Induced voltage pulse and Faraday's law of induction with Cobra4 Xpert-Link

Principle and equipment

Principle

Keywords

Coil, induction, voltage surge, alternating voltage, magnetic field lines, magnetic flux density, oriented surface, scalar product, magnetic flux.

Principle

A permanent magnet falls through a coil at different speeds and the induced voltage surge is measured. The aim of this experiment is to show that the entire induced voltage remains constant during the fall, i.e. that it is independent from the speed.

Tasks

1. Observe the induced voltage when a magnet falls through a coil.
2. Examine the induced voltage for different orientations of the magnet.
3. Determine the influence of the number of turns of the coil on the induced voltage.
4. Determine the influence of the height of the fall on the induced voltage.

Fig. 1: Experiment set-up

Equipment

Position No.	Material	Order No.	Quantity
1	Cobra4 Xpert-Link	12625-99	1
2	Tripod base PHYWE	02002-55	1
3	Support rod, stainless steel, l = 500 mm	02032-00	1
4	Right angle clamp PHYWE	02040-55	4
5	Light barrier, compact	11207-20	2
6	Coil holder	06528-00	1
7	Coil, 3600 turns, tapped	06516-01	1
8	Universal clamp	37715-00	1
9	Glass tube, outer d = 12 mm, inner d = 10 mm, l = 300 mm	45126-01	1
10	Magnet, d = 8 mm, l = 60 mm	06317-00	1
11	Adapter, BNC-plug/socket 4 mm	07542-26	1
12	Connecting cord, 32 A, 750 mm, red	07362-01	1
13	Connecting cord, 32 A, 750 mm, black	07362-05	1
14	Connecting cord, 32 A, 1000 mm, red	07363-01	2
15	Connecting cord, 32 A, 1000 mm, yellow	07363-02	2
16	Connecting cord, 32 A, 1000 mm, blue	07363-04	2

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Set-up and procedure

Set-up

Set the experiment up as shown in Fig. 1:

- Fasten the support rod in the tripod base.
- Fasten the following components on the same side of the support rod in the following order from the bottom to the top: light barrier – coil holder – light barrier – universal clamp. To do so, fasten them to the support rod by way of several right-angle clamps as follows:
  Attach the right-angle clamps with the opening on the square surface to the support rod and tighten them to lock them in place (see Fig. 2). The two clamps for holding the light barrier point backward with the stems of the light barriers being inserted from below. Contrary to that, the clamps for holding the coil holder and universal clamp point forward. Their stems must be inserted from above (see Fig. 3). If everything is arranged correctly, the screws for fastening to the support rod are all located on the same side, one above the other.

  IMPORTANT: In order to ensure that the magnet can fall correctly through the light barriers and coil, we strongly recommend aligning the right-angle clamps as described above.

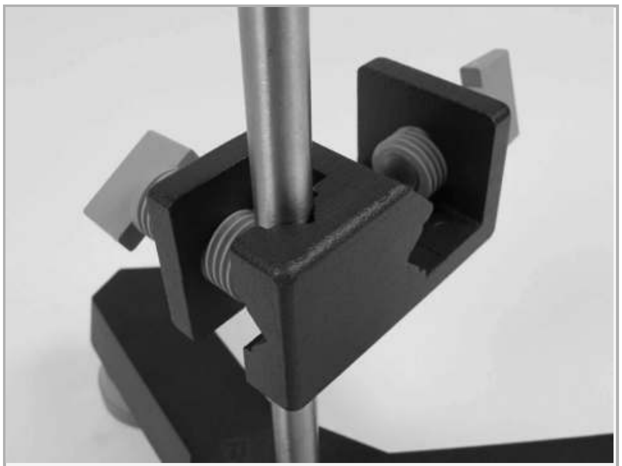

Fig. 2: Right-angle clamp on the support rod for holding the coil holder and universal clamp

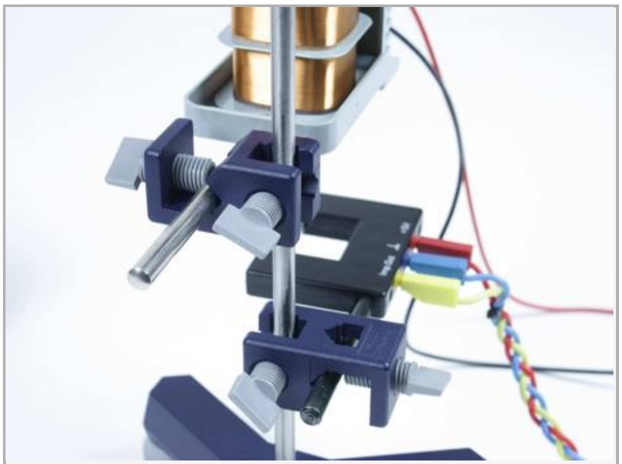

Fig. 3: Clamps for holding the light barriers (bottom) and coil holder/universal clamp (top) in the right-angle clamps

- Align the components vertically with one another:
  - The lower light barrier should be located as close to the tripod base as possible.
  - Arrange the lower surface of the coil holder at a distance of approximately 1.5 times the length of the magnet from the light barrier.
  - Attach the coil to the coil holder.
  - Arrange the upper light barrier at a distance of approximately half of the length of the magnet from the coil.
  - Attach the universal clamp directly above the light barrier.
- Lay the glass tube through the coil and fasten it in the upper end of the universal clamp so that it points perpendicularly to the floor (see Fig. 4). The glass tube provides guidance to the magnet and ensures that it falls without spinning even from greater heights. In addition, it is ensured that the magnet interrupts the light barriers during its fall.

Fig. 4: Passage of the glass tube through the light barriers and the coil

- The light barriers are also used for starting and stopping the measurement data recording process. For this purpose, they must be connected to the Cobra4 Xpert-Link.
  Connect the upper light barrier to the "T1" sockets on the left and the lower light barrier to the "T2" sockets on the right. In doing so, connect the yellow sockets of the light barriers to the yellow sockets of the measuring instrument, the red sockets to their red counterparts, and the blue sockets of the light barriers to the white sockets of the Xpert-Link.
  Then, turn the light barriers around the support rod so that the glass tube is located in the middle of their beam path.
- In order to perform the experiment in a reliable manner, the magnet must interrupt the light barriers during its fall, but the light barriers themselves must not be influenced by the glass tube (e.g. due to refraction, reflection, etc.). The correct alignment can be checked by way of the Xpert-Link as follows:
  - Plug the adapter with the BNC plug to the BNC socket of the voltage input "CH 3" and connect it to the yellow and white socket of the control input "T1" of the Xpert-Link (and, thereby, to the upper light barrier) (see Fig. 5).
  - Connect the Xpert-Link to the computer via the USB cable and open measureLAB. Observe the analogue display of the channel "CH 3" and turn the glass tube with its clamp around the support rod so that it is still located in the beam path and that a voltage of $|U| > 3.6\ \mathrm{V}$ is indicated. Shading of the light barriers by the glass tube with ($U \approx 0\ \mathrm{V}$) must be avoided.
  - Then, connect the voltage input to the yellow and white socket of the control input "T2". Maintain the position of the glass tube. Instead, turn the lower light barrier until a value of $|U| > 3.6\ \mathrm{V}$ is indicated.

Fig. 5: Calibration of the upper light barrier with the Xpert-Link

- As a last step, connect the voltage input "CH 3" of the Xpert-Link to the two outer taps of the coil.

Note

In order to avoid a strong impact of the magnet when it hits the floor, catch it with your hand. Alternatively, a soft pad can be placed under the opening of the glass tube in order to dampen the impact.

Procedure

Start the measurement data recording process in measureLAB.

- To activate the measurement device, select the Xpert-Link on the right panel and lock it.
- Select the correct measurement range. Choose the Xpert-Link in the right panel and press the gear wheel symbol. Select a range of 10 V for channel "CH 3" and apply the settings.
- For automated measurement, set a start trigger on input "T1" to falling edge and a stop trigger on input "T2" to rising edge. Apply these settings.

1. Press the start button. The measurement will not commence straight away. It must be triggered by the upper light barrier (triggered measurement data recording). In order to ensure the same height of fall for all repetitions, hold the magnet at its centre and insert it by half into the glass tube from above with the red side (north pole) downwards. Then, release the magnet and catch it under the coil. The measurement will stop automatically when the magnet reaches the second light barrier.
2. The aim of the second measurement is to examine the influence of the orientation of the magnet. Press the start button again and let the magnet fall through the glass tube as before, but this time with the green end (south pole) downwards.
3. The aim of the third measurement is to examine the effect on the voltage when the coil has only half the number of turns. For this measurement, the tap in the middle of the coil and the lower socket of the coil must be connected to "CH 3" of the Xpert-Link, and the tap in the middle and the upper socket for another measurement.
4. The aim of the fourth part of the experiment is to determine the effect of the height of the fall. For this purpose, push the glass tube in the universal clamp further upwards until the lower end is located approximately on the same level as the upper edge of the coil. Align the glass tube so that the magnet can pass through and, thereby, trigger the lower light barrier when it leaves the glass tube. Activate the measurement by pressing the start button and let the magnet (with any side downward) fall through the glass tube. If the measurement does not stop automatically, it can also be stopped manually by way of the stop button.

Observation and evaluation

Observation

The fall of the magnet induces a voltage in the coil, which is noticeable in the positive as well as in the negative direction. The second reading is always greater than the first one.
When the magnet falls with its other end downwards, the sign of the induced voltage is reversed.
When the number of turns of the coil is reduced by half, the induced voltage is also reduced. When the voltage is measured via the lower half of the coil, the readings occur later and the peak-to-peak distance is greater than in the case of a measurement in the upper half of the coil.
A greater height of fall results in a greater maximum voltage.

Evaluation

The voltage curve can be described by way of Maxwell's third equation or, more precisely, with Faraday's law of induction. It says that a time-varying magnetic field causes an electric rotational field:

$$\oint_{\partial A} \vec{E} \cdot \mathrm{d}\vec{s} + \left(\iint_A \frac{\partial \vec{B}}{\partial t} \cdot \mathrm{d}\vec{A} \right) = 0,$$

with the electric field strength $\vec{E}$, magnetic flux density $\vec{B}$, surface $\vec{A}$, and line element that is tangent to its boundary curve $\mathrm{d}\vec{s}$.
This means that the electric field strength along a closed conductor loop is proportional to the magnetic flux density that suffuses the surface that is enclosed by the conductor loop.
When the permanent magnet enters the area of the coil, the closed magnetic field lines, which run from the north pole of the magnet to its south pole, cross the cross-sectional area of the coil. Due to the fall of the magnet, its relative position with regard to the coil changes and, thereby, also the magnetic field that is active in this area. In accordance with the law of induction, this produces an electric field along the coil. This results in an induced voltage

$$U = -N \cdot \frac{\mathrm{d}\Phi}{\mathrm{d}t},$$

between the two ends of the coil. This voltage is proportional to the number of turns N of the coil and to the variation of the magnetic flux Φ over time. The magnetic flux, on the other hand, describes the magnetic flux density $\vec{B}$ that suffuses the cross-sectional area $\vec{A}$. In the present case, this virtually corresponds to the scalar product of the quantities:

$$\Phi = -\frac{1}{N} \int U \mathrm{d}t = \vec{B} \cdot \vec{A}.$$

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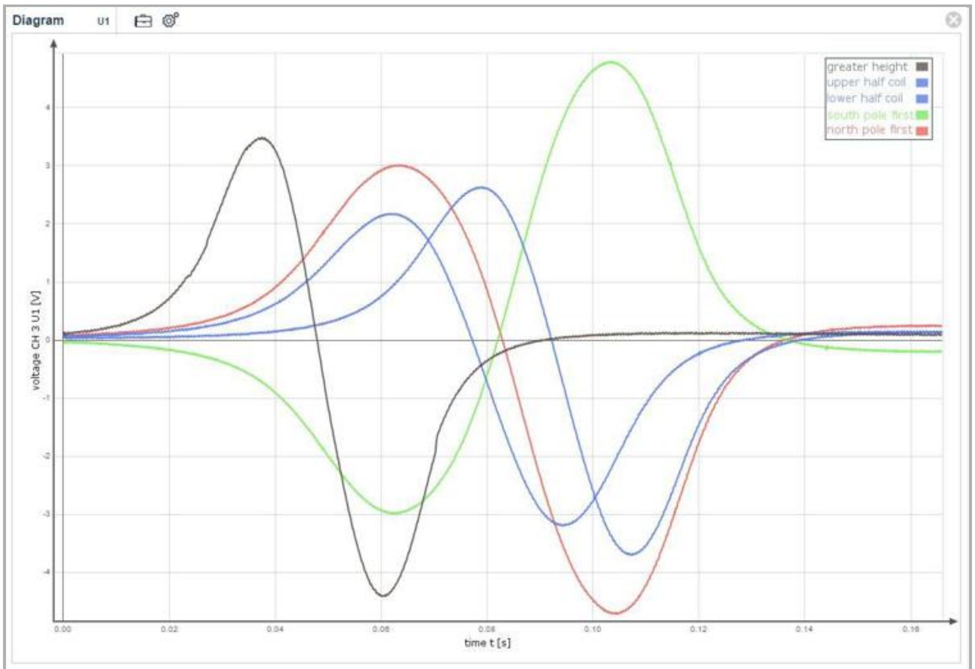

Fig. 6: Measurement example including different orientations of the falling magnet (red and green), a reduced number of turns of the coil (blue), and a greater height of fall once again with a reduced number of turns (black)

1. *Behaviour when passing through the coil*

   At the beginning of the first measurement (compare Fig. 6, red curve), an increase of the induced voltage can be observed. Due to the approaching magnet, an increasing number of field lines cross the cross-sectional area of the coil, leading to growing magnetic flux and, thereby, to an increasing induced voltage.
   Once the magnet has completely entered the coil, all of the field lines that exit the magnet at its north pole and enter the magnet at its south pole cross the cross-sectional area of the coil. As a result, the magnetic flux reaches a maximum and remains constant until the magnet leaves the coil. During this phase, the change in magnetic flux over time and, thereby, also the induced voltage are zero.
   When the magnet exits the coil, the magnetic flux in the coil decreases. This change over time leads to an induced voltage once again, but this time with the opposite sign.
   In addition, it can be noted that the values of the voltage maxima when the magnet enters and exits the coil differ from one another. It must be taken into consideration that, while the magnet falls through the coil, it is continuously accelerated by the earth's gravity field. Due to the higher speed of exit, the change in magnetic flux over time and, thereby, also the induced voltage is greater. At the same time, this change takes place over a shorter period of time so that the area under the two parts of the curve is identical in accordance with the law of induction.

2. *Reversed orientation of the falling magnet*

   If the magnet falls through the coil from the same height but with the south pole downwards instead of the north pole, the qualitative profile of the induced voltage surge is identical. The voltage, however, has the opposite sign (green curve in the example measurement). Since field lines always run from the north pole to the south pole, they now cross the cross-sectional area A of the coil in the opposite direction. This results in a reversed magnetic flux [text]\Phi[/tex] and, thereby, in an opposite induced voltage.

3. *Reduced number of turns*

   The two blue curves of the example measurement were recorded with half the number of turns. Since the induced voltage U is proportional to the number of turns N,
   the area under these curves is also half of the area under the curves with the full number of turns.
   The offset of the curves and the difference in voltage maxima can, once again, be explained by the increasing speed of the magnet. While the magnet reaches the lower half of the coil at a later time and passes through it in less time, the maximum voltage increases.

4. *Greater height of fall*

   The black curve in Fig. 6 has been recorded with a considerably greater height of fall and half the number of turns of the coil (compare the blue curve). It becomes obvious that the maximum induced voltage increases considerably when the speed increases. Due to the reduced duration of influence of the magnet on the coil, the integral over the induced voltage

$$\int U \mathrm{d}t = -N \cdot \Phi = N \cdot |B| \cdot |A|$$

is constant. It depends solely on the magnetic flux density, the cross-sectional area of the coil, and its number of turns.

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Application

An important area of application of induction that is caused by changing magnetic flux is a generator that converts mechanical power into electrical power. The measurement curves strongly resemble an often desired sinusoidal alternating voltage. In the present experiment, deviations such as the distortion of the measurement curve and the increase in amplitude are caused by the accelerated movement of the magnet and the resulting higher change in magnetic flux over time. If the permanent magnet oscillated through the coil at a constant speed and a steady change of direction, it would produce a sinusoidal alternating voltage.
A simple AC generator can be realised by way of a bar magnet that rotates around its centre. If it is brought near a coil, its north pole and south pole alternately face a conductor loop at constant frequency, thereby inducing an alternating voltage in the conductor loop.