Exploring the Magnetic Field of a Slinky

Aim:

To measure the magnetic field inside a slinky solenoid. Find the relationship of the field to the density of turns in the coil and to the current through the solenoid. Calculate the value of μ_0 from these relationships

Equipment:

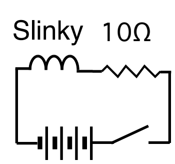
1. Slinky
2. Metre stick
3. 3 ring stands
4. DC Power Supply or 4 D Cells and A 4-Cell battery holder
5. 10 Ω resistor (or similar size)
6. SPST switch
7. LabPro Interface and LoggerPro Software
8. Magnetic Field Sensor
9. Voltage Probe

Procedure

1. Put a slinky over a metre stick and stretch it from end-to-end so that the turns are separated and there are several mm between each turn. Two turns per centimetre works well. You may need to gather some turns together at each end. Clip each end of the slinky to the metre stick

(Unlike this picture shows, put the metre stick inside the slinky and hang it horizontally from ring stands. Pictures courtesy of Memorial University Physics Dept.)

2.Start with four batteries in a holder and connect the negative side to one end to the slinky. The positive side should be connected through a switch to a 10Ω resistor and then to the other end of the slinky.

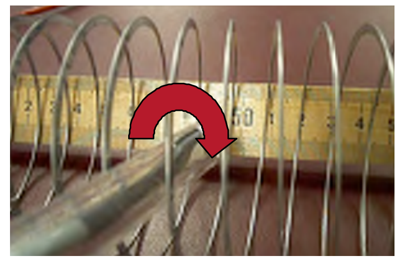


3. The 10 Ω resistor serves to limit the current and can be used to monitor the current with a voltage probe. (I = V/R) The slinky itself has a resistance of several ohms and you should measure it.

4. Connect the Magnetic Field Sensor to the LabPro, connect the voltage sensor across the 10 Ω resistor and to the LabPro. Start Logger Pro and verify that both voltage and magnetic field readings appear on the screen.

5. Poke the magnetic field probe through the loops near the middle of the slinky and orient the probe to sense the field along the axis of the slinky. The probe measures the field passing normal to the white dot. (Some probes have a pivot.) Measure the field inside the slinky with no current flowing. Secure the probe in place. You can now zero the probe by clicking the "ZERO" icon, or alternately, just note the value of the field with no current. (Call this the "ambient" field.)

6. Close the switch and make a note of the increase in field and the current. (The current in A is 1/10th of the voltage reading in volts across the 10Ω resistor.) After you verify that it works, open the switch, start data collection, and, when you see the baseline, close the switch to record the field increase and the current.



7. Explore the field inside the slinky. Is it nearly constant from place to place? Is it oriented along the slinky's axis? Try to estimate the accuracy of the magnetic field measurement. Does the current in the slinky produce any field outside the slinky?

8. Fix the probe in place so it can measure the field inside the slinky for several current values without being moved. Make sure it is aligned to measure the field parallel to the slinky's axis.

9. Complete a table of current vs magnetic field for four values of current obtained with 4, 3, 2 and 1 D cell. Estimate the error in each measurement based on the variability of the field measurement when you think the probe is placed properly.

10. Plot a graph of magnetic field vs current with error bars. Fit a straight line through the points. (By hand or machine, as you wish.) Only allow a non-zero y-intercept if the data show a clear offset from strict proportionality. Any non-zero y-intercept represents a systematic error. Find the constant of proportionality (the slope) and estimate its uncertainty. Determine μ_0 and estimate the uncertainty. Does your value of μ_0 agree with the theoretical value ($4\pi \times 10^{-7}$ N/A^2) within the uncertainty?

11. Put the four batteries back in and verify that the field is nearly the same as it was before. (Be careful. If you have been leaving the current on for long periods of time, the battery voltage will soon start to droop.)

12. **Optional:** Now measure the magnetic field for about five values of *n* (turns/m) . You can use the original measurement with four cells as your first measurement. Take four more field measurements with the slinky stretched or squeezed to a different turn density. Try to vary the turn density as much as you can—at least a factor of two. Small changes may not show a clear trend. Make a table of your values (including the first) with estimated uncertainties.

    Plot a graph of magnetic field vs *n*, with error bars. Fit a straight line and find the constant of proportionality again. Estimate the uncertainty in the proportionality constant.

    Determine μ_0 from both of your straight-line fit and estimate the uncertainty. Do they it with the other experimentally determined value?

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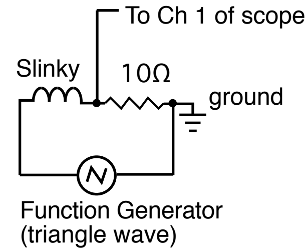
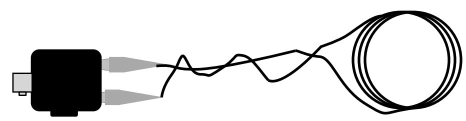
Electromagnetic Induction in a Slinky

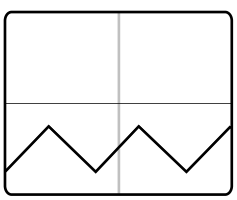


1. Mount the slinky on a metre stick as you did in the previous exercise. Replace the battery with the function generator: connect the ground of the function generator to the 10 Ω resistor and the signal end to the end of the slinky that is not connected to the resistor. The ground side of the function generator should be connected to one end of the resistor. You don't need a switch, it's included in the function generator.

2. Use oscilloscope channel 1 to monitor the voltage across the 10 Ω resistor . Clip the x10 probe to the resistor on the end closest to the slinky. The ground of the probe should be the same as that of the function generator, i.e.,the other end of the resistor.



3. Make a pick-up coil by winding 10 turns of 22-gauge wire around a form with a definite area of several cm^2. Leave enough wire on both ends of the loop so that the ends can be striped and connected to alligator clips which are attached to a BNC-banana (male-male)-plug adaptor. The wire between the loops and alligator clips should be twisted to avoid noise pickup. Use a BNC cable to connect the "induction probe" to the oscilloscope's channel 2. Make sure channel 1 is set to x1.



4. Adjust the function generator to make a triangle wave of 1 kHz at maximum amplitude. Display the ch 1 signal, the voltage across the 10 Ω resistor, on the bottom half of the oscilloscope screen with a time scale that shows about two or three complete cycles. The trigger source should always be ch 1.

5. Now slip the pick-up coil inside the slinky and align the axis of the loops with the axis of the slinky. Use the most sensitive scale on ch 2 to pickup the emf induced in the loops. The signal is quite small and probably has a lot of noise in it. You can improve the signal/ratio by signal averaging as follows: press the "Acquire" button and then press the button beside "Average". This will now cause the oscilloscope to display the average of several sweeps. The reduction of the random noise signal is just like averaging independent measurements to reduce random error. You can control the number of sweeps used in the average. Little signals with big noise require more sweeps be averaged. There is a downside to signal averaging, namely, increasing the number of sweeps that are averaged decreases the responsiveness of the scope to changes.

6. Once you get a good display of current on the bottom, and induced emf on the top, make an accurate sketch of the scope display. Make sure to write down all relevant parameters such as the time scale and the voltage scales of both channels. Also record the area of the loop and the number of turns/m of the slinky. The frequency, slinky current and induced emf voltage can be determined from your sketch of the display.

7. Explore how the orientation of the loops of the pick-up coil affects the signal. Align the axis parallel to the slinky's axis. Then turn loops backward from the way they were at first. What orientation makes the signal larger, smaller, upside-down etc?

8. Calculate the amplitude you expect on channel 2, the induced signal, from the frequency and,amplitude of the driving signal and number of turns in your induction probe. You may follow the calulation outline in the Activity Guide but the formulae must be modified for the slinky geometry.

$$\frac{d\Phi^{\mathrm{mag}}}{dt} = \pm\mu_0 n A_p \frac{dI}{dt}\cos\theta = \pm\mu_0 n A_p 2f(I^{\mathrm{max}} - I^{\mathrm{min}})$$

where n is the number of turns/m of the slinky, the angle between the axes of the slinky and pick-up coil, θ, is 0 and the pick-up coil has area A_{p}. Also f is the frequency of the triangle wave and (I^{max} – I^{min}) is the peak-to-peak current going through the slinky. So the signal measured by the pick-up coil is given by

$$\mathcal{E} = N_p \frac{d\Phi^{\mathrm{mag}}}{dt}$$

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where N_{p} is the is the number of turns in the pick-up coil.

9. Now explore how the amplitude of the signal picked up depends on frequency: In addition to 1 kHz, measure 100 Hz and 10 kHz. Do you see the trend? Make a table of your data and plot a graph of amplitude vs frequency. I suggest a log-log scale would be appropriate for this. How can you explain the frequency dependence in terms of Faraday/s law?

10. As a final test remove the coil from the slinky, unwind it and wrap it around the outside of the slinky and reconnect to see if you can get any induction when the loop surrounds the outside of the slinky. Remember that ideally the magnetic field produced by the slinky is only inside the coil and there should be almost no varying magnetic field outside it.

11. With all the data and observations from this experiment you should be able to make a good story about Faraday's Law for your formal report.

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