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Development of a metal detector for smartphones and its use in the teaching laboratory

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Abstract
In this article, we describe how to develop an inductive metal detector that can be integrated to any Android or iOS smartphone with a standard audio port at low cost. The results indicate the metal detector can be used in the physics teaching laboratory as a practical application of principles of electromagnetism. It allows one to differentiate ferromagnetic samples from the diamagnetic and paramagnetic ones and can also be used to investigate the direction of alternating magnetic fields and to demonstrate the Faraday's cage shielding effect.

1. Introduction

The data-processing power of smartphones grows larger each year, including ever-more sophisticated software and hardware features. To explore this potential and increase the interactivity of these devices with the outside world, manufacturers have been including diverse types of sensors, such as biometric sensors, barometers, accelerometers and Hall effect sensors among others. Because of this evolution, the use of smartphones as tools for exploring various physical phenomena in educational contexts is increasing [1–3].

Many experimental research proposals for acoustic phenomena have been exploring the audio capabilities of smartphones, using, for example, tone-generator apps to produce sound waves with well-defined frequencies [4–6] or using the fast Fourier transform (FFT) technique to perform real-time sound analysis [7, 8].

Another approach is to use the audio circuit of these devices to analyze electrical signals injected through the headphone jack; this technique allows one to visualize the waveform of the electrical signals similarly to an oscilloscope [9]. However, in this case care must be taken that the voltage levels in the studied circuits do not exceed the limits supported by the smartphone's audio port.

In this article, we will show an alternative method that greatly simplifies the interface with the audio circuit and guarantees the integrity of the smartphones. From it, we will describe how to construct an inductive metal detector that permits the accurate detection of small metal objects, even allowing to differentiate ferromagnetic metals from the diamagnetic and paramagnetic ones.

Finally, we will show that the device we have developed allows one not only to demonstrate the operation of a metal detector in a clear and didactic way, but also lends itself to other demonstrations and investigations of electromagnetism concepts, proving to be a versatile tool for the physics teaching laboratory and a low-cost alternative to the traditional approach that involves the

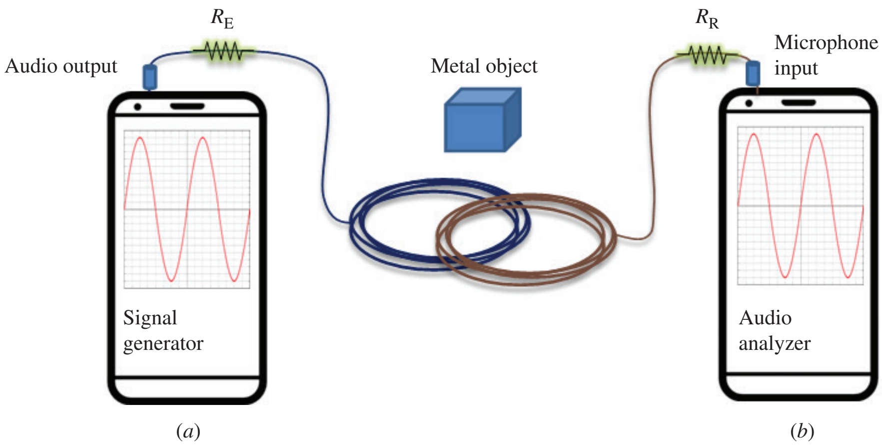

Figure 1. Structure of the inductive metal detector: (a) emitter circuit and (b) receiver circuit.

use of an oscilloscope and a tone generator for similar demonstrations [10].

2. Experimental method

2.1. Experimental setup

The inductive metal detector presented here bases its operation on both an emitter circuit and a receiver circuit (see figure 1). The emitter circuit uses the audio port of a smartphone to power a coil of magnet wire with alternating current, generating a variable magnetic field near this coil. The receiver circuit is formed by a second coil connected to the microphone input of another smartphone; it has the role of detecting the small fluctuations in the electromotive force (emf) induced in the receiver coil due to the variable magnetic field created by the emitter coil.

The emitter and receiver circuits are independent; the coils are superposed, but there is no electrical connection between them. The R_E and R_R resistors are used to match the impedance of the coils to the impedance of the smartphones audio port.

When the components are arranged according to figure 1, an electrical signal can be seen in the receiver circuit whenever the emitter circuit is activated. In addition, when we put a metallic object near the coils, eddy currents are induced in the object itself, these currents, in turn, create a magnetic field that opposes the magnetic field that gave rise to them; this causes a fluctuation in the magnetic field that results in a tiny change in the emf induced in the receiver circuit. Finally, this change in the signal will indicate the presence of metal nearby.

Both emitter and receiver circuit used audio apps to produce and visualize the signals. In our tests, the apps used for signal generation and detection were, respectively, Simple Tone Generator [11] and SmartScope [12], available for free for Android devices. The Apple iOS apps and the full compatibility of the metal detector with this system are discussed throughout the text and in section 5.

Figure 2 shows the screenshot of the apps as well as the coils that were connected to the smartphones during the tests. Figure 2(b) shows the waveform recorded on the receiver device as a response to a 6500 Hz signal in the emitter circuit.

2.2. Determination of the coil turns number

For the metal detector to work properly, we must ensure that the emitter coil would generate a sufficiently strong emf on the receiver coil so the audio circuit can register it.

The induced electromotive force on the receiver coil (ε) can be expressed as a function of the mutual inductance between the coils (M) and of the current that flows through the emitter coil (I) [13], as follows:

$$\varepsilon(t) = -M\frac{\mathrm{d}I(t)}{\mathrm{d}t}. \tag{1}$$

Since in our circuit we will use a sinusoidal alternating current, we can write $I(t)$ as a function of the angular frequency (ω), current amplitude I_0 and phase (φ), as:

Figure 2. Apps' screenshots and the detector coils. (a) Simple Tone Generator, (b) SmartScope and (c) emitter (left) and receiver (right) coils.

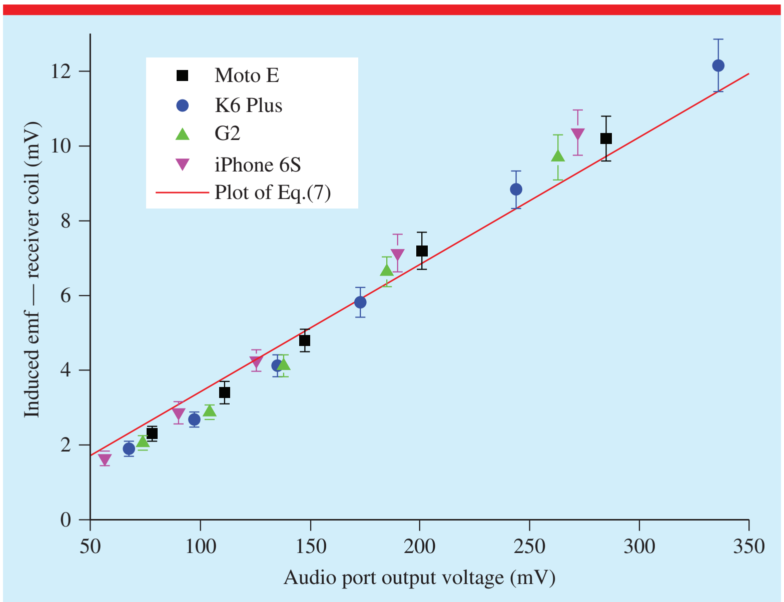

Figure 3. Induced emf on the receiver coil versus voltage applied by each smartphone on the emitter coil through the audio port. Smartphones used in the tests: Motorola Moto E, Lenovo K6 Plus, LG G2 and iPhone 6S.

$$I\,(t) = I_0 \text{ sen}(\omega t + \varphi). \tag{2}$$

Differentiating equation (2) with respect to time and substituting it into (1), we obtain

$$\varepsilon(t) = -MI_0\ \omega\cos(\omega t + \varphi). \tag{3}$$

From equation (3) we see that the maximum amplitude of the induced emf can be expressed as

$$\varepsilon =\ MI_0\ \omega, \tag{4}$$

where the mutual inductance (M) depends on the geometry of the coils and the material medium in which they are.

In our project, we will use two coplanar circular coils of the same diameter. Since the magnetic field produced by a circular loop of current-carrying wire is not homogeneous over the loop surface, the value of M could be found by elliptic integrals as demonstrated by Maxwell [14]. However, for our purpose we do not need such mathematical sophistication, instead we will use an approximate expression [15]. In this case, the mutual inductance can be expressed as:

$$M = \mu_0 N_{\mathrm{E}} N_{\mathrm{R}} a \left\{ \left(1 + \frac{3}{16}\frac{b^2}{a^2}\right) \ln \frac{8a}{b} - \left(2 + \frac{b^2}{16a^2}\right) \right\}, \tag{5}$$

where $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$ is the magnetic permeability of the vacuum, a is the common radius of the coils and b is the distance between them. The parameters N_E e N_R were included to consider the number of turns of the emitter and receiver coils, respectively.

To make the coils we used magnet wire (number 21 AWG) and a PVC tube adapter as a form with a diameter of 1.5″ (38.10 mm) therefore we have for the coil radius $a = 19.05\,\mathrm{mm}$. For the distance between the coils we adopted $b = 6.90\,\mathrm{mm}$. Thus, when we replace these values in equation (5), we obtain:

$$M = 0.022\,15\mu_0 N_\mathrm{E} N_\mathrm{R}. \tag{6}$$

By inserting the above expression in equation (4), we have:

$$\varepsilon = 0.022\,15\mu_0 N_\mathrm{E} N_\mathrm{R} I_0 \omega. \tag{7}$$

At this point, to simplify the assembly of the detector, we will adopt the same number of turns on both coils, that is, $N_\mathrm{E} = N_\mathrm{R} \equiv N$, in this case, the previous expression can be rewritten as:

$$N = \sqrt{\frac{\varepsilon}{0.022\,15\mu_0 I_0 \omega}}. \tag{8}$$

To determine N so that the coils can produce a detectable signal, we will use some reference values from the Android compatibility definition document. According to these specifications, the 3.5 mm audio jack must be able to drive at least 150 mV of output voltage on a 32 Ω speaker impedance [16], i.e. Android smartphones must provide at least 4.69 mA of current under this condition, this will be our parameter I_0 in equation (8).

For the desired induced emf we will adopt $\varepsilon = 5\,\mathrm{mV}$, a value that can be easily detected by the ADC (analog-to-digital converter[1]) circuit of the smartphones [17] and that is far from the saturation threshold thereof, which varies greatly between different devices, ranging from 12 mV to 38 mV in laboratory tests [18].

For the detector oscillation frequency, we will use 6500 Hz (remember that $\omega = 2\pi f$). Since microphones can typically work with frequencies ranging from 20 Hz to 24 kHz, the choice of the specific frequency adopted in this range is a matter of convenience.

We can now determine N replacing the above parameters in equation (8), thus obtaining

$$N \cong 31\ \text{turns}.$$

To summarize, $N = 31$ is the number of turns that the detector coils must have to guarantee a 5 mV signal at the ADC circuit input, whenever the emitter circuit is supplied with 150 mV. Obviously, this is the standard condition that every Android smartphone must satisfy, but in practice their audio circuits are able to explore a wide range of intensities below and above this value.

3. Results

3.1. Validation of the physical model

To evaluate the accuracy of our model, we assembled two coils according to the parameters specified in the previous section. One of the coils, connected in series with a 32 Ω resistor, was connected to the audio port of a smartphone, the other coil was placed concentrically over the first one and both had their terminals connected to the channels of an oscilloscope, this way, we could register the voltage level provided by the smartphone to the emitter coil and the induced emf in the receiver coil simultaneously.

Four smartphones from different manufacturers were used in the measurements. To adjust the voltage level in the audio port we used the volume button of the smartphone. The results obtained are shown in figure 3, the symbols correspond to the data and the red line to the plot of equation (7).

As can be seen from figure 3, there is an excellent fit of the data to the model. The induced emf in the receiver coil not only presents a linear behavior as a function of the voltage supplied by the audio port, but also its maximum value is within the typical saturation limits of the ADC circuits of the smartphones [18], which ensures that the devices will not be damaged by overvoltage.

To show the compatibility of our approach to different hardware and software platforms we also included in figure 3 the data obtained using an iPhone 6S as a signal generator. In this case, we used the app Audio Function Generator [19]

1 The analog signal provided by a microphone (or, in our case, by the receiver coil) needs to be converted to a digital signal before it can be handled by the smartphone. The circuit responsible for this conversion is called ADC.

Table 1. Emf values indicated by the app SmartScope for coaxially superposed coils when we placed metallic objects near them.

Object	emf read by the app SmartScope[2] (mV)	Percent change (relative to air)	Dimensions of the object (mm)
Air	244.0	0.0	—
Stainless steel coin	262.0	+7.38	$\varnothing = 23$ $h = 2.7$
Iron cylinder	260.5	+6.76	$\varnothing = 12.7$ $h = 40$
Ferrite rod	286.0	+17.21	$\varnothing = 10$ $h = 40$
Aluminum cylinder	226.3	-7.27	$\varnothing = 12.7$ $h = 40$
Aluminum block	216.3	-11.37	19.3 x 12.9 x 32.2

to produce the audio signal. More details will be discussed in section 5 at the end of this article.

3.2. Testing the metal detector

We will use some metalic samples to test the sensitivity of the metal detector. Basicaly, if we put some ferrous object near or inside the coils the high magnetic permeability of them will intensify the magnetic field inside the coils, thus increasing the signal strength. On the other hand, in the case of diamagnetic or paramagnetic samples the opposite magnetic field produced by eddy currents inside the samples will result in a sinal decrease [10].

We can use different apps to detect these changes in signal strength, so we can have a visual or auditory alert that indicates the presence of metal. In fact, it is possible to distinguish ferromagnetic metals from the other ones.

In the following tests, we used the app SmartScope [12] to display the signal from the metal detector. Table 1 shows the change in signal strength when different metal objects were placed near the center of the detector coils.

Many of the tested items have produced a change in the emf of the receiver coil of about 7% relative to the absence of metal (air core coils), which is not too large but can be perceived without difficulty.

Obviously, the signal fluctuation depends on several factors, including the shape of the object,

[2] Since the app SmartScope was not calibrated, the values of the emf in this column are not related to the measured values shown in figure 3, however, for our purpose we are interested only in the relative intensity of the signal with respect to the air core coils.

Table 2. Emf values indicated by the app SmartScope while the detector coils were positioned tangentially when we placed metallic objects near them.

Object	emf read by the app SmartScope (mV)	Percent change (relative to air)
Air	31.08	0.0
Stainless steel coin	45.32	+45.84
Iron cylinder	38.08	+22.53
Ferrite rod	62.38	+100.8
Aluminum cylinder	25.80	−16.98
Aluminum block	25.42	−18.20

its volume and what it is made of. For example, when we used a ferrite rod (whose magnetic permeability is much larger than that of iron) we obtained an increase of about 17% in the signal intensity with respect to air, which was easily noticed by the wave-amplitude change during the experiment. For the aluminum objects (paramagnetic material) we obtained a decrease in the signal that varied between 7% and 11%.

The reason we have only small fluctuations of the signal is closely related to the design of our detector: with coaxially superposed coils, the emitter coil induces a much stronger emf in the receiver coil than the small effect caused by eddy currents, that is, the problem is that we are trying to detect tiny electrical fluctuations within a much more intense signal.

There is a straightforward way to improve the signal-to-noise ratio in our experiment, making it easier to see the detection signal. This trick consists in sliding one of the coils relative to the other so that they are no longer coaxial, although

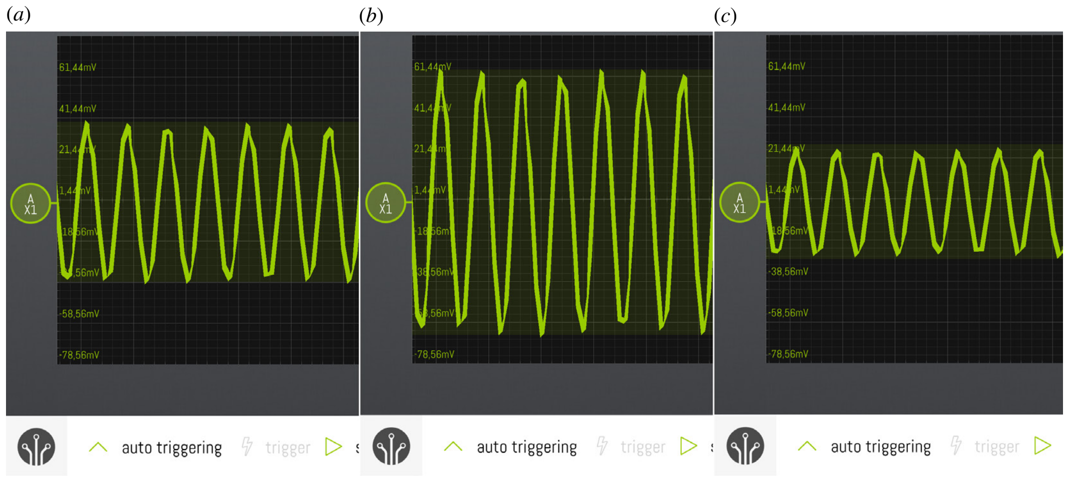

Figure 4. The App SmartScope showing different signal amplitudes in three cases: (a) when there are no metallic objects near the coils, (b) when we bring close the coin used in the tests and (c) when we bring close the aluminum block. The images were cut to the right so they could be placed side by side. The same vertical and horizontal scales were used in the three situations presented.

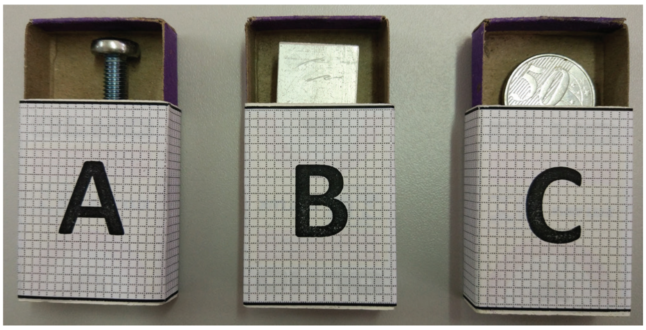

Figure 5. Boxes with hidden items inside them. Sample A: iron screw, sample B: aluminum block, sample C: steel coin.

they are still in the same plane. This is exactly what is illustrated in figure 1. Then, the metal object will be put near the region where the coils partially overlap or touch each other.

The reason for the benefits of this approach is that when we slide one of the coils relative to the other, the total magnetic flux on the receiver coil decreases because this coil will be crossed by both internal and external field of the emitter coil which are opposite in direction, making it easier to perceive the signal of metallic objects [20].

To illustrate this behavior, we show in table 2 the emf values indicated by the app for the same metallic objects when the coils were displaced until they were tangential to each other. The metal objects were positioned right above the contact point of the coils.

As we can see in table 2, the change in the relative intensity of the signal was significant being twice as large for the aluminum cylinder and up to six times greater for the coin, when compared to table 1, for example.

Figure 4 shows the screenshot of the app SmartScope in three different moments to demonstrate the great visual contrast caused in the wave amplitude when putting metallic objects near the coils.

As we mentioned earlier, it is possible to use several different apps to interpret the detector signals, making the experiment very flexible. For example, we can also get an audible alarm for the presence of metal near the coils. In this case we can use the app Noise Meter [21] by calibrating a threshold for the 'noise' level that would trigger

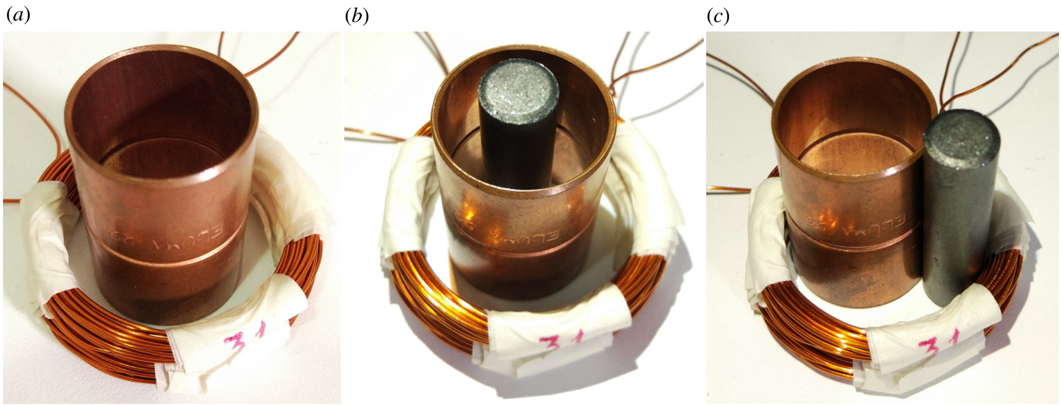

Figure 6. Steps to demonstrate the shielding effect of a metal tube. (a) A copper tube inside the detector coils causes the signal to decrease. (b) The introduction of a ferrite rod inside the tube does not change the signal. (c) The introduction of the rod by the outside of the tube increases the signal intensity.

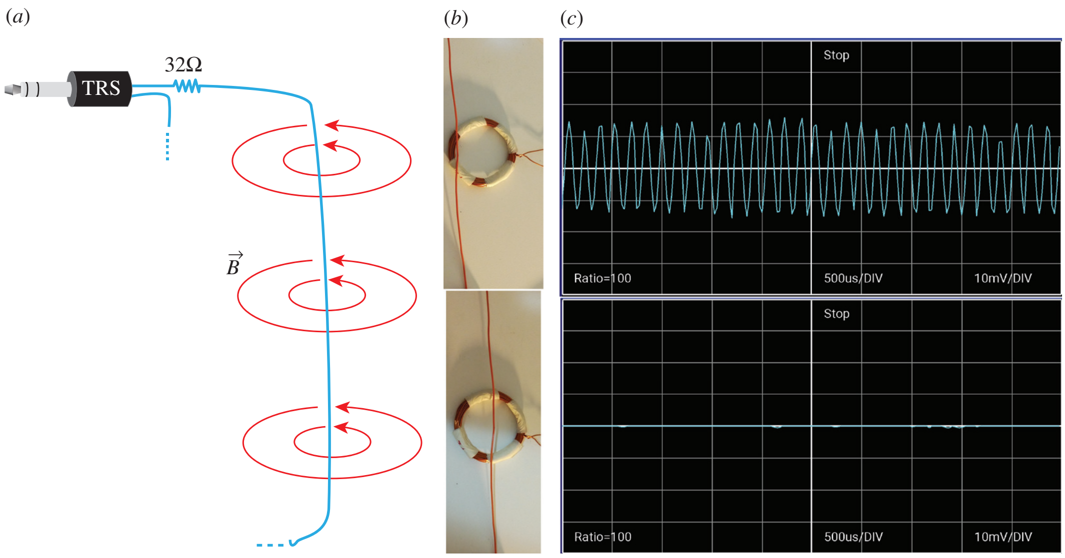

Figure 7. Investigating the magnetic field of a straight wire carrying alternating current (6500 Hz). (a) Straight wire replacing the emitter coil. (b) Receiver coil in various positions relative to the wire. (c) Signal detected by the app Oscilloscope [22] when the receiver coil was positioned as indicated in (b).

the alarm sound, but remember that what the app means by 'noise' is, in fact, the base signal of our detector.

4. Suggestions for use of the metal detector

We will describe here some of the several ways that the metal detector can be used in exploratory and motivating activities in the study of electromagnetism.

4.1. How does a metal detector work?

A search for 'metal detector' in the Play Store (Android) or App Store (iOS) will bring dozens of results with apps that claim to implement the functionality of a metal detector. However, there is a flaw in these apps: none of them can detect aluminum or copper objects, for example.

The reason for this is that these apps do not detect metal objects but the magnetic field created by them, basing their operation on the Hall effect sensor of the smartphones. Due to the Earth's magnetic field it is common for iron objects to exhibit residual magnetization stronger enough to be detected.

This flaw of the apps would be used to start a discussion around the topic: 'How does actually a metal detector work?'.

4.2. Classification of hidden items

A simple activity that encourages teamwork and helps students remember the basic categories of magnetic materials (ferromagnetic, paramagnetic and diamagnetic) is to classify hidden objects from the response of the metal detector, and so separating these objects into two groups: on one side the ferromagnetic ones, on the other, paramagnetic and diamagnetic ones.

In the end, the students should reveal the contents of the boxes and verify if they were correct in their classification. Figure 5 shows how this activity can be done with matchboxes and simple objects.

4.3. Confronting an electrostatic shield

Another interesting activity is to introduce a copper (diamagnetic) tube in the center of the detector coils, as a result, the intensity of the detected signal decreases rapidly. Then ask students what will happen to the signal if we introduce the ferrite rod (or iron rod) into the copper pipe? Usually, the students' guess is that the signal will grow again. However, the experiment reveals that the signal strength remains unchanged!

The explanation, however, is simple: the tube acts as a Faraday cage, preventing the induction of eddy currents in what is inside. To demonstrate this, just pass the rod by the outside of the tube: the signal will intensify again. Figure 6 illustrates this demonstration.

4.4. Investigating the direction of the magnetic field of a straight wire

With a minor change in our project we can use the metal detector to explore some characteristics of alternating magnetic fields.

If we replace the emitter coil by a segment of straight wire, we can detect an induced emf whose intensity will vary according to the position of the receiver coil relative to the wire, as shown in figure 7.

Whenever the total magnetic flux through the receiver coil is zero, the signal will be lost, see figures 7(b) and (c) (lower), respectively. Otherwise, the flux will be detected, see figure 7(c) (upper). This technique can be used in the teaching laboratory to map the direction of the magnetic field produced by circuits in their vicinity.

5. iOS Compatibility

To evaluate the compatibility of our metal detector with the Apple iOS system we used an iPhone 6S.

Connecting the iPhone 6S to the emitter circuit, tests demonstrated that our device was recognized as a valid 'audio' device, allowing us to use the app Audio Function Generator [19] to produce the 6500 Hz signal. The equivalence between the voltage levels produced by Apple and Android devices was verified (see figure 3).

We also tested the iPhone 6S as a signal receiver, connecting its audio input to the receiver coil and using the free app SignalScope X [23] to monitor the signal. The results were fully compatible with those obtained with Android devices.

In fact, this iOS compatibility was already expected, since our device uses only the audio port to communicate with the smartphones, so these devices cannot differentiate it from a common headset, which, as we know, can be used on both Android and Apple devices.

6. Conclusions

In this paper we described how to build a low cost inductive metal detector for smartphones that exploits the audio systems of these devices to generate and interpret the alternating electrical signals used in its operation.

The measured electrical signals agree with the theoretical model and confirm the safeness of the proposed metal detector.

We also demonstrated how to extend the usage of this device by using different apps for both Android and iOS platforms. This was only possible due to the universality of the headset port among smartphones, which demonstrates the robustness of our approach.

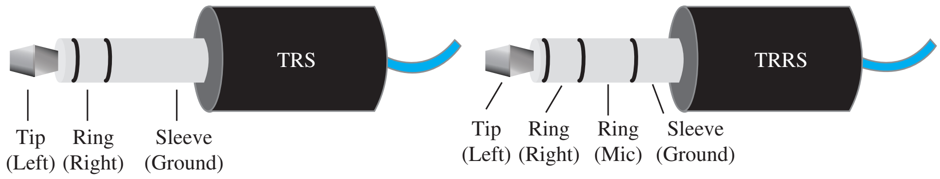

Figure A1. TRS (Tip-Ring-Sleeve) and TRRS (Tip-Ring-Ring-Sleeve) plugs with audio and microphone connections indicated for Android devices. For the iOS system, Mic and Ground connections are inverted in the TRRS connector, which does not affect the metal detector functionality.

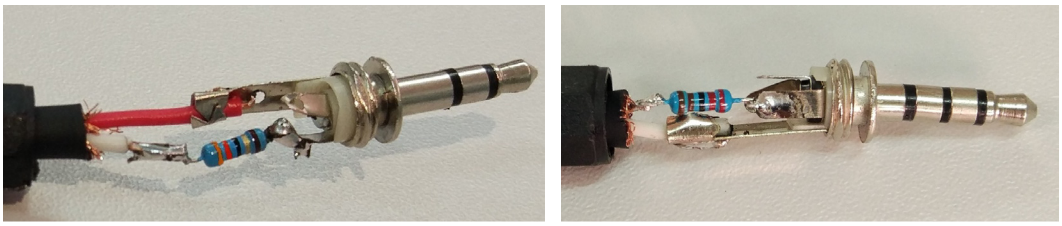

Figure A2. Electrical connections. (a) TRS with 32 Ω in series (to the audio output) and (b) TRRS with 2.2 kΩ in series (to the microphone input).

Finally, we presented cases in which the metal detector can be used in the teaching laboratory, motivating students' interaction in groups and allowing them to review and discuss electromagnetism topics, all through active exploration using smartphones.

We believe that the presented metal detector can be used in physics teaching laboratory activities with significant learning potential, both as a practical demonstration of basic principles of electromagnetism and as a useful tool in exploratory activities of various electromagnetic phenomena.

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Appendix

A.1. Electrical connections

By default, smartphones use a 3.5 mm audio port that accepts TRS and TRRS connectors as indicated in figure A1. The only difference between the two is that the TRRS plug includes an extra ring for microphone connection in addition to the right and left audio channels.

We used a TRS plug for the emitter circuit and a TRRS for the receiver. In this case, one terminal of the emitter coil must be connected to an audio channel (left or right) of the TRS plug and the other to the 'ground' (Sleeve). In addition, in the receiver circuit, one end of the coil must be connected to the microphone terminal (Mic) of the TRRS plug and the other to the 'ground' (Sleeve). The electrical connections can be seen in figure A2.

To ensure that the coils will be recognized by the smartphones as standard audio devices, both circuits must follow the audio specifications for Android devices which recommends that the headphones should have an impedance between 32 and 300 Ω, while the microphone should have a resistance of 1000 Ω or greater [24].

For our assembly we use a 32 Ω resistor in serious with the emitter coil and a 2.2 kΩ resistor with the receiver coil. These resistors can be incorporated into the audio cables for a more compact assembly, as shown in figure A2.

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