Metal detection and the Theremin in the classroom

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Abstract

A classroom demonstration is described that shows a method for detecting nonmagnetic metals. The demonstration uses the simple and sensitive beat oscillations technique and employs off-the-shelf equipment usually available in most physics laboratories. More than 80 years ago, the beat oscillations technique was used to design the first electronic musical instrument, the famous Theremin. The demonstration set-up also serves as a Theremin. Metal detection and the Theremin are attractive topics for student projects.

Introduction

The detection of metals has become more important than ever before. Everyone is subjected to such detection, for example at airports. The aim of the demonstration described here is to acquaint students with a metal-detecting technique that is appropriate for either magnetic or nonmagnetic metals. Here we consider detecting nonmagnetic metals. The same principle was used, more than 80 years ago, to design the first electronic musical instrument, the famous Theremin. This topic is also considered in the demonstration.

The design of the Theremin has been described in many places. In particular, Skeldon *et al* [1] described two versions of this instrument. The present apparatus is much simpler because it employs off-the-shelf equipment usually available in most physics laboratories. The set-up for the demonstration of metal-detecting and melody-playing may be assembled in 20 minutes. For the demonstration, one needs an oscilloscope, a high frequency oscillator, an audio amplifier with a loudspeaker, a search coil, a semiconductor diode, four resistors and one capacitor.

The detection of nonmagnetic metals is based on positioning a conducting sample in an AC magnetic field. According to Faraday's law, the AC field creates an EMF and eddy currents in the sample. The eddy currents modify the magnetic field in the sample. For a sample of simple geometry the changes in the magnetic field can be used for contactless determinations of the electrical resistivity of metals and semiconductors (see, e.g., [2, 3] and references therein).

Several techniques have been developed for detecting the eddy currents induced in a conducting sample. Of these, the beat oscillations technique is very simple and sensitive. It is easy to explain this technique and to use it in a demonstration of detecting metals using common and inexpensive equipment.

Beat oscillations technique

The beat oscillations technique involves two high frequency oscillators (figure 1). One of them contains a search coil, whose inductance, along with the capacitance of the LC circuit, governs its resonance angular frequency according to the Thomson formula, $\omega_1 = 1/\sqrt{LC}$. An alternating current flowing through the search coil creates a magnetic field around it. When the coil is placed near a metal sample, the eddy currents in the sample affect the magnetic field and thus the inductance of the coil and the frequency of the

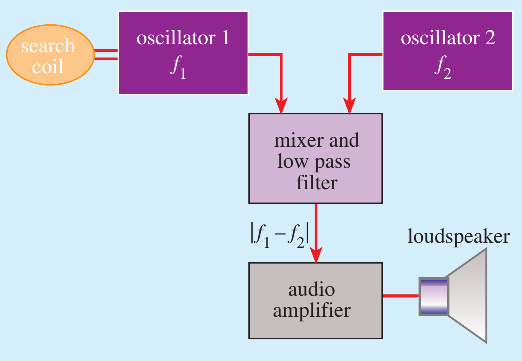

Figure 1. Block diagram of beat frequency apparatus for detecting metals.

oscillator. The change in frequency depends on the geometry of the sample and on the electrical resistivity of the metal. The second oscillator has a constant but adjustable frequency, ω_2.

The signals from both oscillators, $A_1 \sin \omega_1 t$ and $A_2 \sin \omega_2 t$, are fed to a device multiplying the two signals (mixer). The result of the multiplication contains voltages of new angular frequencies, $|\omega_1 - \omega_2|$ and $\omega_1 + \omega_2$:

$$A_1 \sin \omega_1 t \, A_2 \sin \omega_2 t = \frac{A_1 A_2}{2}[\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t].$$

Now it will be more convenient to deal with the usual frequencies, $f = \omega/2\pi$. The frequency of the second oscillator, f_2, is set to make the difference frequency, $|f_1 - f_2|$, be in the audio range. A low-pass filter suppresses signals of high frequencies. The audio signal is amplified and then fed to earphones or a loudspeaker. New frequencies also appear when two high frequency voltages are fed to a nonlinear device, e.g. a semiconductor diode. Due to the nonlinearity of its I–V characteristic, the output current contains, along with components of the main frequencies f_1 and f_2, components of additional frequencies, generally given by $|n_1 f_1 \pm n_2 f_2|$, where n_1 and n_2 are integers. The amplitudes of these components may be very different, according to the characteristic of the nonlinear device. For a quadratic I–V characteristic, the diode current is proportional to

$$(A_1 \sin \omega_1 t + A_2 \sin \omega_2 t)^2 = A_1^2 \sin^2 \omega_1 t + 2A_1 \sin \omega_1 t \, A_2 \sin \omega_2 t + A_2^2 \sin^2 \omega_2 t.$$

The first and the third terms on the right-hand side of this equality are of doubled frequencies, $2\omega_1$ and $2\omega_2$, while the second term contains components $\omega_1 + \omega_2$ and $\omega_1 - \omega_2$.

The frequency of the audio signal obtained is very sensitive to a piece of metal close to the search coil. Let us suppose, for instance, that the frequencies of the two oscillators are of the order of 10^6 Hz, while the difference frequency is in the range 10^2 to 10^3 Hz. In this case, the human ear can detect frequency changes of the order of 10 Hz, which equals 0.001% of the high frequency governed by the inductance of the search coil. With electronic frequency meters, the sensitivity may be much better, being limited only by the stability of the high frequency oscillators.

Experiment

The demonstration set-up is very simple (figure 2). It employs equipment usually available in most physics laboratories. As the search coil, we use a 200 turn coil from Pasco Scientific [4] (catalogue index EM-6711). The radius of the coil is 10.5 cm. The coil is connected to the input of an amplifier. The capacitance of the amplifier's input and of the connecting cable forms the capacitance of the LC circuit. As the amplifier, we use an oscilloscope, Kenwood model CS-4025. One of its channels has an output terminal and provides gain up to 10^2. The output of the oscilloscope is connected to the coil through a 50 kΩ resistor. This positive feedback compensates for losses in the LC circuit and causes continuous oscillations in it.

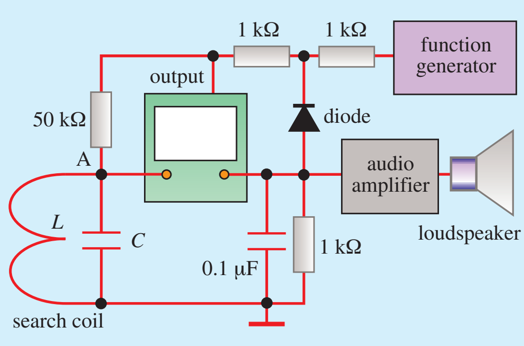

Figure 2. Diagram of the set-up for detecting metals. The output resistances of the oscilloscope and of the function generator should be taken into account. In our case, they equal 50 Ω.

The signal of frequency f_1 taken from the output of the oscilloscope is fed to a semiconductor diode, which acts as a nonlinear device. A function generator, Good Will model GFG-8020G, provides the signal of frequency f_2. Any other high frequency oscillator could be used. A parallel RC circuit, placed as the load of the diode, reduces all high frequency components of the output voltage and retains the audio component. This component proceeds to an audio amplifier and then to a loudspeaker. It is also fed to the second channel of the oscilloscope and is seen on its screen. The audio signal may appear even without a special nonlinear device, when the two high frequency signals are fed to the audio amplifier. In this case, the nonlinearity of the amplifier itself provides the necessary nonlinear operation.

After assembling the set-up, it is necessary to set the gain of the oscilloscope for triggering continuous oscillations in the LC circuit and to tune the function generator to obtain a sufficiently low difference frequency. The frequency f_2 may be set to be higher or lower than the initial frequency of the first oscillator. It should be remembered that a nonmagnetic sample causes a decrease in the inductance of the search coil, in accordance with Lenz's law. The frequency f_1 thus increases. In our case, this frequency is nearly 58 kHz. The audio signals are heard when the frequency f_2 is set near to 29 kHz ($2f_2 \approx f_1$), 58 kHz ($f_2 \approx f_1$), or 116 kHz ($f_2 \approx 2f_1$). Additional signals are produced due to the interactions of the harmonics of the main frequencies. The higher the operating frequency, the higher the sensitivity of the set-up.

As the sample, we use an aluminium alloy plate 2 mm thick. This plate, when brought close to the search coil, produces very significant changes in the beat frequency. It is useful to demonstrate that the effect of the sample is maximum when the plate is parallel to the plane of the coil. This configuration allows the production of the largest eddy currents in the plate and thus the greatest influence on the magnetic field and the inductance of the search coil. In our case, the maximum change in the beat frequency amounts to about 1 kHz. When the plate is placed perpendicular to the plane of the coil, its small thickness does not allow for high eddy currents. This demonstration shows why the magnetic cores of common transformers contain many thin sheets.

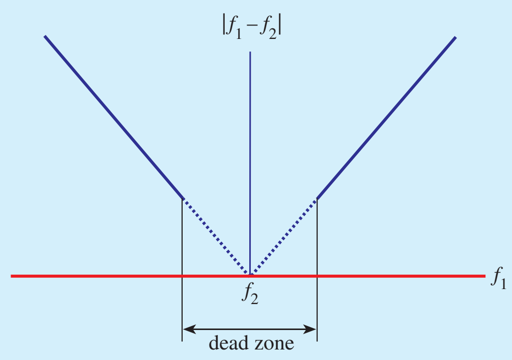

Figure 3. Due to the synchronization (locking) effect, a dead zone appears, where the two frequencies, f_1 and f_2, become equal because of the coupling between the oscillators.

Bulk magnetic cores are made of ferromagnetic materials of high electrical resistivity.

If two oscillators of similar frequency are coupled to each other, a specific phenomenon occurs, the synchronization (locking) of the oscillators. When the frequencies fall into a narrow frequency range, they converge into one frequency. For beat frequency oscillators, this means the appearance of a dead zone, in which the beat frequency remains zero regardless of the tuning of the oscillators (figure 3). To obtain good sensitivity, the dead zone should be reduced to a minimum. This can be achieved by decreasing the coupling between the oscillators.

When detecting magnetic materials, the magnetic field in the sample and thus the inductance of the search coil increase. Usually, this effect is stronger than that due to the electrical resistivity of the sample. Therefore, the change in the beat frequency is opposite to that when finding a piece of nonmagnetic metal.

A homemade search coil can be used instead of the coil from Pasco. The number of turns of the coil may be much less, say 50. In this case, the frequency of the oscillators and thus the sensitivity of the set-up would be even higher.

The Theremin

In 1920, the Russian radio engineer Lev Termen (1896–1993) designed a beat frequency device as an electronic musical instrument. In Russia, the instrument was named Termenvox, i.e. the voice of Termen. Beginning in 1925, Lev Termen (known

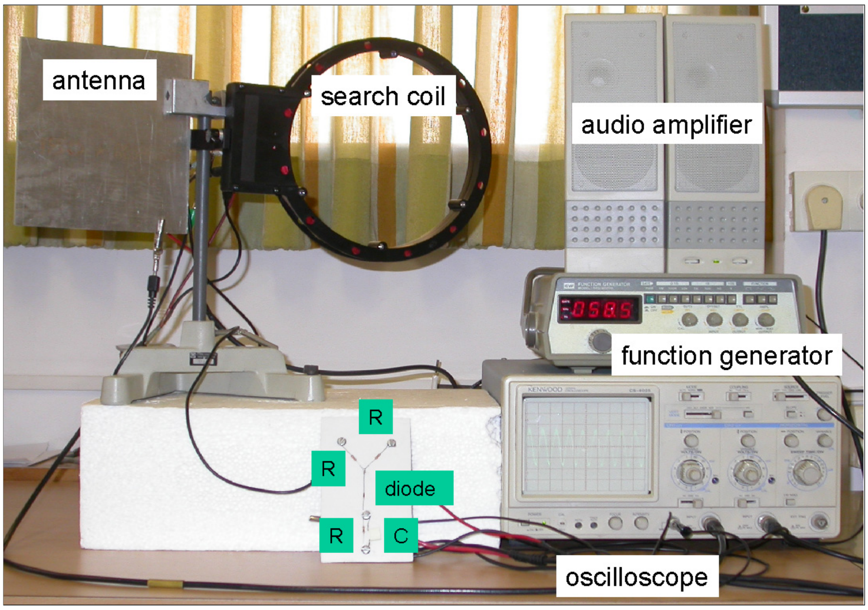

Figure 4. Arrangement for metal detection and melody-playing. $R = 1$ kΩ, $C = 0.1$ μF.

also as Léon Théremin) took his instrument on tour around Europe and the USA. At that time, it was indeed amazing to see a mysterious instrument played without any physical contact with the performer. The pitch of the instrument was controlled by the proximity of the player's hand to an antenna. The other hand controlled the sound volume, also without physical contact.

Termen spent about ten years in New York developing electrical musical instruments, the Theremins, until he suddenly vanished without trace in 1938. Termen was thought to be dead, but after many years he was found in Moscow. His fantastic story, with the crucial role of the KGB, may be found elsewhere (see, e.g., [5] and references therein, and articles on the internet).

After considering the beat oscillations technique and metal-detecting, it is easy to explain the operation of the Theremin. Clearly, the difference frequency depends also on the capacitance of the LC circuit of one of the high frequency oscillators. For this purpose, an antenna, a rod or a metal plate should be electrically connected to the LC circuit and positioned conveniently for the player. The antenna should be well isolated from the ground. The player's hand can be considered as a grounded conductor. Its position near the antenna affects the capacitance of the LC circuit and thus the frequency of the audio signal. The player's other hand controls the sound volume by changing the frequency of an additional beat frequency oscillator. This beat frequency is translated into voltage, which governs the gain of the audio amplifier. After a short period of training, a musician was capable of playing simple melodies with this instrument.

The synchronization (locking) of the high frequency oscillators of the Theremin is very undesirable. For reproducing low frequencies, the dead zone should not exceed 100 Hz.

To play melodies with the above metal-detecting apparatus, it is sufficient to arrange an antenna, a metal plate connected to the point A in figure 2. Our demonstration set-up provides two possibilities for governing the audio frequency: either by a piece of metal near the search coil or by a hand near the antenna plate (figure 4).

Theremins, as well as beat frequency oscillators and metal-detecting tools, are commercially available. A beat frequency oscillator employing LC circuits can immediately be adapted to play melodies. For this purpose, it is sufficient to add an antenna to the LC circuit of one of the high frequency oscillators.

Conclusion

Returning to metal detection, it is worth mentioning that there are some additional options for detecting ferromagnets. Ferromagnets display a variety of distinctive properties, which are more informative than the electrical resistivity of nonmagnetic metals. For instance, the magnetization curve of a ferromagnet, i.e. the dependence of the magnetization on the external magnetic field, may be very individual. This provides a way of distinguishing between keys in a customer's bag and a thin magnetic label fixed to goods in a shop. An intriguing question is how to disable the magnetic label at the cash desk after purchase and how to restore the label if necessary.

Metal detection and the Theremin are attractive topics for student projects. Abundant information about both items can be found on the internet.

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Professor Yaakov Kraftmakher received his PhD and DSc degrees from the USSR Academy of Sciences, Novosibirsk (1963) and the Institute for Metal Physics, Sverdlovsk (1968). He summarized his main works in the books *Lecture Notes on Equilibrium Point Defects and Thermophysical Properties of Metals* (World Scientific, 2000) and *Modulation Calorimetry* (Springer, 2004).