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Tools and setups for experiments with AC and rotating magnetic fields

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Abstract

A rotating magnetic field is the basis for the transformation of electrical energy to mechanical energy. School experiments on the rotating magnetic field are rare since they require the use of specially prepared mechanical setups and/or relatively large, three-phase power supplies to achieve strong magnetic fields. This paper proposes several experiments and describes setups and tools which are easy to obtain and work with. Free software is offered to generate the required signals by a personal computer. The experiments can be implemented in introductory physics courses on electromagnetism for undergraduates or specialized courses at high schools.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The force on a current carrying wire in a magnetic field is the basic phenomenon used in conversion from electrical to mechanical energy. The AC (alternating current)-powered motors are based on the rotating magnetic field. Such a field has a constant value, but its orientation changes linearly with time. The principles of the rotating magnetic field were first explored and used by Nikola Tesla [1].

Basic experiments on electromagnetism in high schools and universities include demonstrations of the Ampère and Biot–Savart laws [2–4]. However, the descriptions of experiments on the rotating magnetic field are rare. The existing descriptions focus on ready-made motors and offer the measurement of torque and velocity under a load [5, 6], and the only persuasive demonstration of a rotating magnetic field may be the well-known ‘Columbus Egg’ experiment, first presented by Nikola Tesla in 1893 [7]. The repetition of this experiment in school is possible, but it involves the use of a complex (commercially available) electromechanical assembly and three-phase drive. Additionally, such a pre-assembled setup lacks the possibility of experimenting, and is potentially dangerous due to high voltages and currents used.

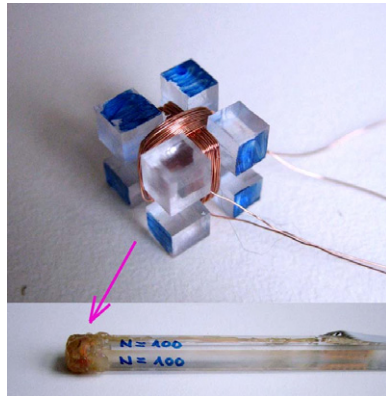


Figure 1. Orthogonal detection coils (top) and the detection wand (bottom).

2. A tool to detect the AC magnetic field

An AC magnetic field can be detected by a coil; the voltage induced in the coil is proportional to the rate of change of the magnetic field, the number of turns in the coil and the cross-section of the coil in the direction of the magnetic field. A home-made detection coil with a cross-section A of about 1 cm^2 and $N = 100$ turns of a thin wire can be connected to an oscilloscope and used for the purpose. The amplitude of the induced voltage is maximal when the axis of the coil is aligned with the direction of the AC magnetic field.

The improved detection tool consists of two detection coils with orthogonal axes, as shown in figure 1. Each coil has $N = 100$ turns of $2r = 0.1 \text{ mm}$ wire. A plastic cube ($10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$) with engraved sides supports the two coils in place. The cube is glued to a longer plastic support and covered with glue to protect the winding. Such a detection wand eases the determination of the field direction and is a useful tool in experiments with rotating magnetic field.

The induced voltages U_x and U_y appear across the terminals of both the coils when the detection wand is placed into the AC magnetic field $B = B_0 \sin \omega t$ with a constant direction, amplitude B_0 and frequency ω :

$$U_x = NAB_0\omega \cos \omega t \cos \beta, \quad U_y = NAB_0\omega \cos \omega t \sin \beta. \quad (1)$$

Here β stands for the angle between the direction of the AC magnetic field and the axis of the x -detection coil. The induced voltages are in phase and proportional to the component of the AC magnetic field, aligned with the corresponding axis of the coil in the wand (figure 2). The induced voltages can be observed by an oscilloscope in the X - Y mode, with two passive RC filters added to attenuate high frequencies. The voltage U_x moves the spot on the screen in the horizontal direction, and the voltage U_y moves the spot on the screen in the vertical direction. When the frequency ω is 50 Hz, the bright spot moves across the screen fast and draws a solid straight line (figure 3). The inclination of the line depends on the angle β , but its length remains constant and proportional to the amplitude B_0 as long as the direction of the magnetic field remains in the plane, defined by the axes of the detection coils.

Digital oscilloscopes are best avoided for these experiments. The fast and non-synchronized sampling in the X - Y mode produces a trace, composed of many small dots. The best results are obtained by analogue oscilloscopes, where the trace on the screen is a

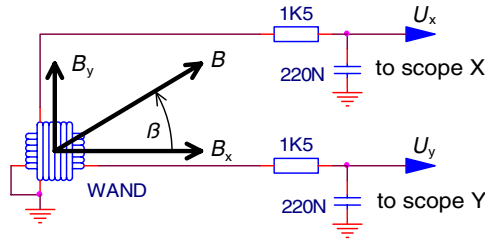


Figure 2. The wand in the magnetic field and passive filtering of induced voltages.

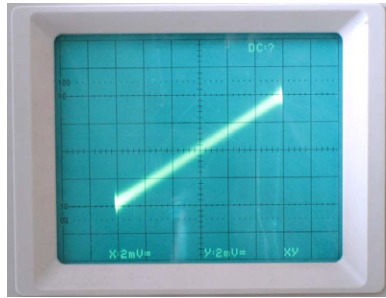


Figure 3. Signal from the detection wand, placed in an AC magnetic field.

solid line. Analogue oscilloscopes additionally provide an easily understandable picture at lower frequencies, since it is clearly seen that the trace is produced by the moving spot.

3. The rotating magnetic field and its detection

A rotating magnetic field can be produced by rotating a permanent magnet as shown in figure 4, where four button-size permanent magnets are glued on a motor. When the motor is energized, the rotating magnetic field is created, and ω_M represents the frequency of rotation. The rotating magnetic field can be described as being composed of two orthogonal components $B_x = B_0 \cos \omega_M t$ and $B_y = B_0 \sin \omega_M t$ with the directions x and y , respectively, that match the axes of the detection coils in the wand. When the wand is inserted in the rotating magnetic field the induced voltages are

$$U_x = -NAB_0\omega_M \sin \omega_M t \quad \text{and} \quad U_y = NAB_0\omega_M \cos \omega_M t. \quad (2)$$

When these voltages are observed with the oscilloscope in the X – Y mode, a circle appears on the screen (figure 5). In some rotating magnetic fields the components B_x and B_y may not be equal to the amplitude B_0 . The circle then degrades into an ellipse, the inclination of the ellipse being dependent on the orientation of the detecting wand in the rotating magnetic field.

The presence of the rotating magnetic field can be simply shown by

- (a) putting a compass above the slowly rotating permanent magnets; the rotation of the compass needle matches the rotation of the permanent magnets; such a phenomenon is used in synchronous motors, or



Figure 4. Permanent magnets are glued to a motor. When rotated they produce a rotating magnetic field and rotate the ring.

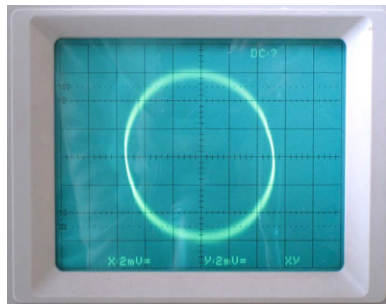


Figure 5. Rotating magnetic field as detected by the wand.

- (b) suspending a non-ferromagnetic ring above the rotating permanent magnets; the rotation of the ring follows the rotation of the permanent magnet, but with lower speed; such a phenomenon is used in asynchronous motors.

The compass used in (a) should have an axle which prevents tilting of the needle or the needle might get stuck. Also, the needle might not follow the rotation of the permanent magnets if they rotate too fast. One can start with a slow speed, and then increase the speed gradually.

The ring used in (b) should be non-ferromagnetic. The effect can be demonstrated also by using a non-ferromagnetic conducting disc; a coin of 20 €c worked well for the author. The ring or coin were glued to a 30 cm long sewing thread and suspended above the permanent magnets, which rotated at about ten turns per second.

The reason for rotation in (a) is obvious: the compass needle is attracted by the rotating permanent magnet and follows its direction. In (b) the reason is less obvious. Suppose the permanent magnets rotate with frequency ω_M , and the ring with frequency ω_R ; then the relative

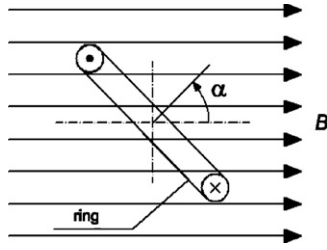


Figure 6. The ring in the magnetic field.

frequency of rotation of the ring in the magnetic field is $\omega_{RL} = \omega_M - \omega_R$. Due to the rotation of the ring in the magnetic field B a voltage U_{IR} is induced in the ring with cross-section A :

$$U_{IR} = A \frac{d}{dt} (B_0 \cos(\omega_{RL} t)) = -A B_0 \omega_{RL} \sin(\omega_{RL} t). \quad (3)$$

At the frequencies used the inductive resistance of the ring is negligible compared to the resistance R of the ring. The induced voltage U_{IR} produces a current I_{IR} which is in phase with the induced voltage. The torque τ on a current carrying ring (figure 6) can be expressed as

$$\tau = B I_{IR} A \sin \alpha. \quad (4)$$

Here α stands for the angle between the direction of the magnetic field B and the axis of the ring. This gives

$$\tau = B_0 I_{IR} A \sin(\omega_{RL} t) = B_0 \frac{A B_0 \omega_{RL} \sin(\omega_{RL} t)}{R} A \sin(\omega_{RL} t) = \frac{\omega_{RL} (A B_0)^2}{2R} (1 - \cos(2\omega_{RL} t)). \quad (5)$$

The frequency of the torque is double the frequency of the rotation of the ring, and always forces the ring to rotate in the same direction. Note that the average value of the torque is proportional to the relative frequency of rotation ω_{RL} , and is non-zero if the ring rotates with a different frequency than the magnetic field.

4. Driving the electromagnets

All AC-driven motors exploit one of the two principles demonstrated in (a) and (b), but use AC-driven electromagnets to create the rotating magnetic field. This paper presents tools to perform various experiments with a rotating magnetic field without the use of potentially harmful voltages and with more options to experiment with. Commercially available coils with iron cores for the demonstration of induction and transformer operation are used. The coils have 300 turns, the cross-section of the core is 30 mm \times 30 mm, and are allowed to draw a maximum current of 4 A. Coils with more turns would produce larger effects.

A rotating magnetic field is produced by electromagnets which are driven by out-of-phase harmonic signals. Such signals with adjustable frequency, amplitude and phase can be generated by a personal computer and a sound card. Up to two out-of-phase signals (LineOutL and LineOutR) can be generated with special software that was written by the author (figure 7). All adjustments can be made on-line without stopping the generation. The complete software including the source code in VB6 is available at the website of the author [8] for free download.

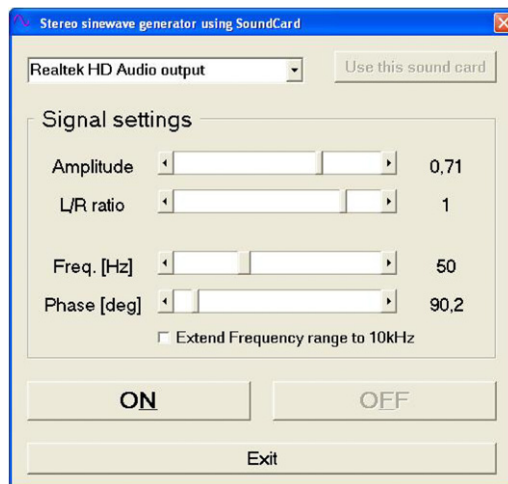


Figure 7. The screenshot of the program that allows the generation of two harmonic signals with the sound card.

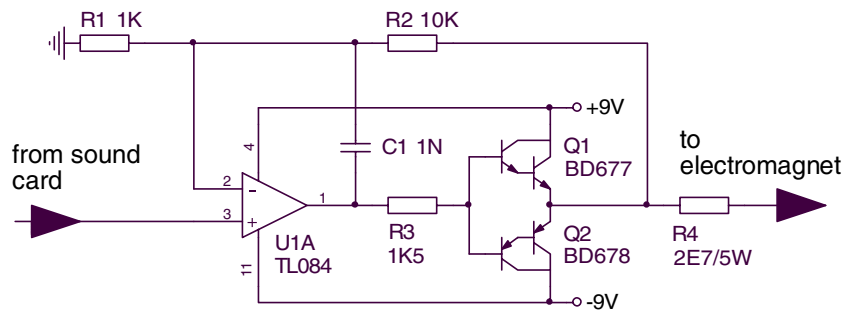


Figure 8. The schematic diagram of the amplifier.

A sound card is capable of generating AC signals in the range of 20 Hz to 20 kHz with amplitudes up to 1 V. The software can generate signals down to 1 Hz, but with reduced amplitude depending on the properties of the sound card.

The signals from the sound card cannot drive large currents. A simple amplifier was assembled on a prototype board to allow the connection of electromagnets. The schematic diagram of the amplifier for a single electromagnet is given in figure 8. It consists of a general-purpose operational amplifier TL081/TL084, two complementary Darlington transistors BD677/BD678 and few passive components (resistors and capacitor). The price for all components should not exceed 5 €. The transistors are mounted on a heat sink, removed from an old computer power supply and the circuit is powered by a general purpose power supply of ± 9 V/3 A. The gain of the amplifier is defined by the ratio of the resistors $(1 + R_2/R_1)$, and can be adjusted to the needs. The components R_3 and C_1 prevent oscillations, and the resistor R_4 is added to prevent the damage in the case of a short circuit at the output. A maximum undistorted harmonic signal at the electromagnet produces a current of about 1 A.

Up to three coils are driven simultaneously in a three-phase system; therefore three driving signals for the electromagnets are needed. The signals have to be delayed for 120° with respect

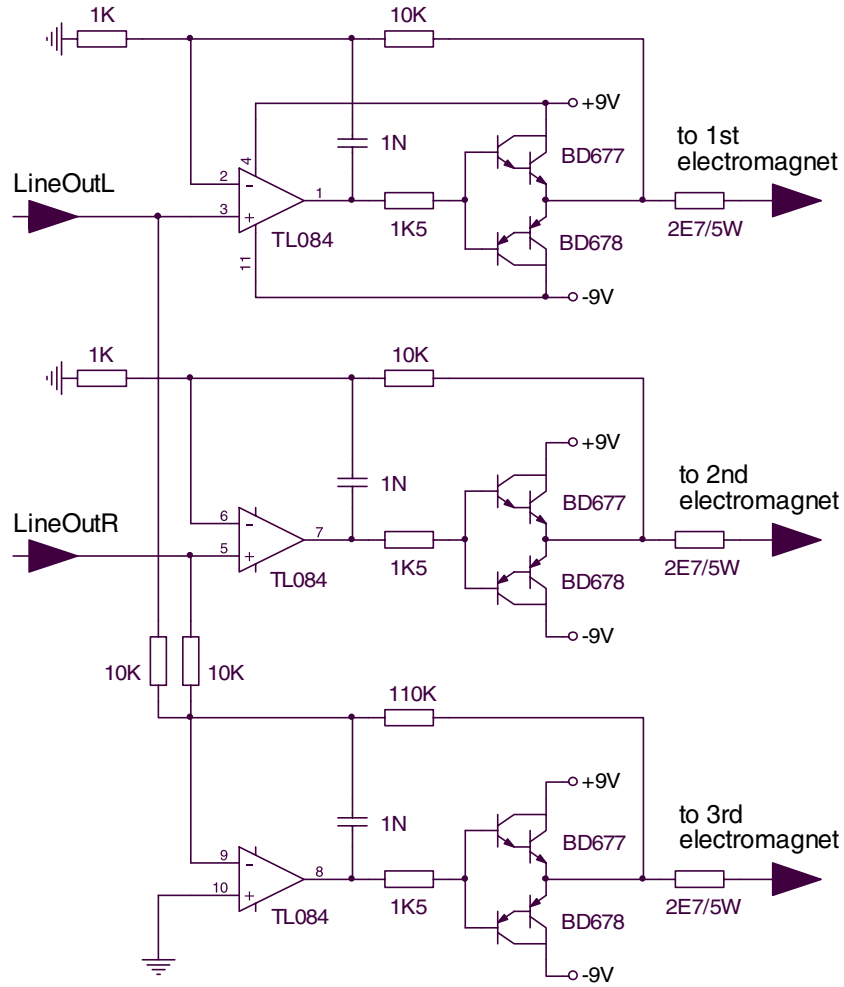


Figure 9. The schematic diagram of the complete three-channel amplifier.

to each other. A sound card can provide only two signals. The third signal is prepared from these two which are 120° out-of-phase signals by adding them together and reversing the polarity of the sum:

$$-[\cos(\omega t + 0^\circ) + \cos(\omega t + 120^\circ)] = \cos(\omega t - 120^\circ). \quad (6)$$

The amplifier shown in figure 8 is expanded and upgraded to accommodate the amplification of the two signals generated by a sound card and the summation-and-inversion to provide the third signal. The complete schematic diagram is shown in figure 9, and the photograph of the assembled system is shown in figure 10. The power supply lines are decoupled by $10\ \mu\text{F}/15\ \text{V}$ capacitors (not shown in figure 9).

Normally, an electromagnet is connected between the output of an amplifier and the ground. Additionally, the upper two channels of the amplifier can be connected in parallel in order to obtain a larger output current to the electromagnet. An electromagnet can alternatively

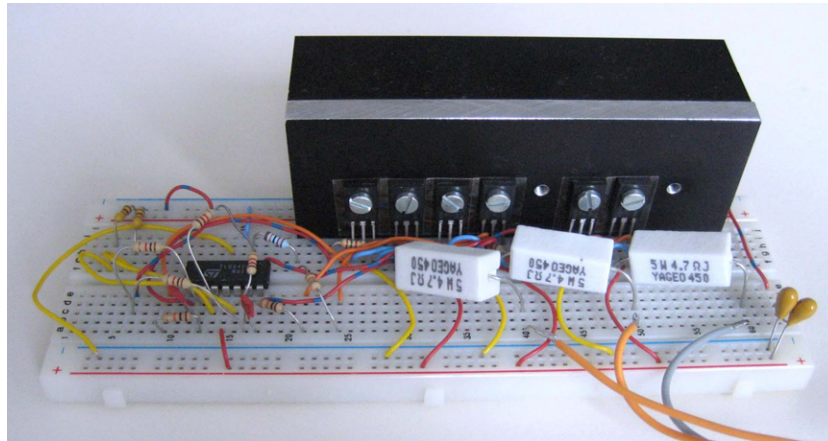


Figure 10. The photograph of the assembled amplifier from figure 9.

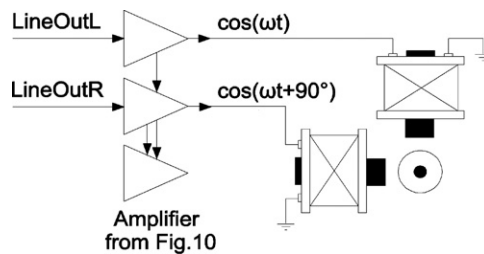


Figure 11. Two electromagnets are driven by the amplifier from a sound card to create the rotating magnetic field; the sound card should provide 90° out-of-phase signals.

be connected between the outputs of the upper two channels, which are driven by 180° out-of-phase signals in order to increase the amplitude of the driving signal.

5. Experiments with the rotating magnetic field

The basic rotating magnetic field can be created by two electromagnets, which are positioned orthogonally as shown in figure 11. These electromagnets should be driven by two signals, which are 90° out-of-phase signals, and are produced by the dedicated software (figure 7). The output signals LineOutL and LineOutR from the sound card are amplified by the upper two channels of the amplifier (figure 9) to drive the two electromagnets.

The presence of the rotating magnetic field can be verified by the detecting wand. The position of the wand where the shape of the beam trace on the screen is optimal (maximum amplitude and most circular-like) should be determined first. Then the compass or the suspended ring should be placed there; and both will rotate.

One can experiment with different frequencies of the driving signals and different positions of the electromagnets. When using a compass one should start with the low frequency of the driving signals, preferably a few Hz only, and then increase the frequency gradually, otherwise the compass needle might not start rotating. When using a suspended ring one can start with a frequency of 50 Hz; at lower frequencies the signal induced in the ring might be too small to

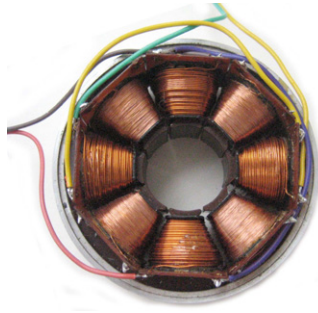


Figure 12. A commercial winding for a two-phase system.

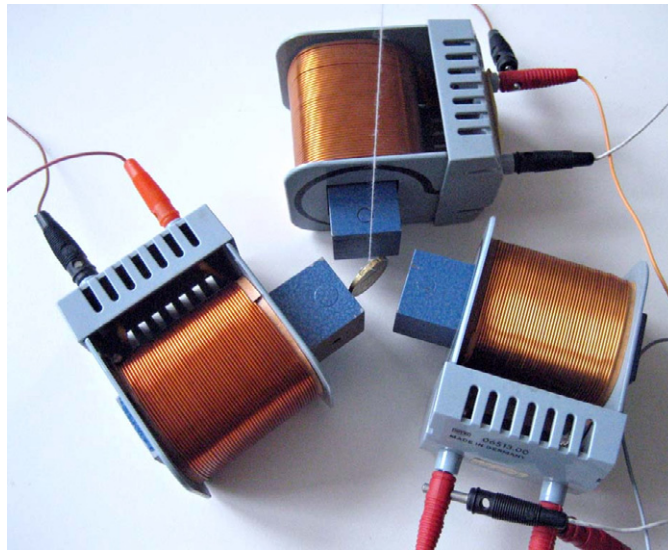


Figure 13. The setup for a three-phase system with three electromagnets.

cause rotation. The rotation will be slow, and will stop once the torque caused by the rotating magnetic field matches the torsion torque of the sewing thread the ring is suspended on.

Commercial motors use symmetrical windings such as the one in figure 12. Here the vertically aligned, opposite pair of coils with darker wires replaces one electromagnet from figure 11, and the horizontally aligned pair of coils replaces the other electromagnet. The outer sides of all coils in figure 12 are mounted on a ferromagnetic material to achieve a stronger magnetic field.

The sum of currents in two-phase systems is not constant, but the electrical system must be designed to withstand maximum currents, and is therefore not optimal. A symmetrical drive with a constant sum of currents can be achieved in three-phase systems with three electromagnets and three driving signals. A photograph of the setup is shown in figure 13. The angle between the electromagnets is about 120° . Electrically, the coils can be connected either in a triangle or star configuration (figure 14). The triangle configuration allows a bigger current through the coils with the same amplitude of the driving signals. Again, the existence

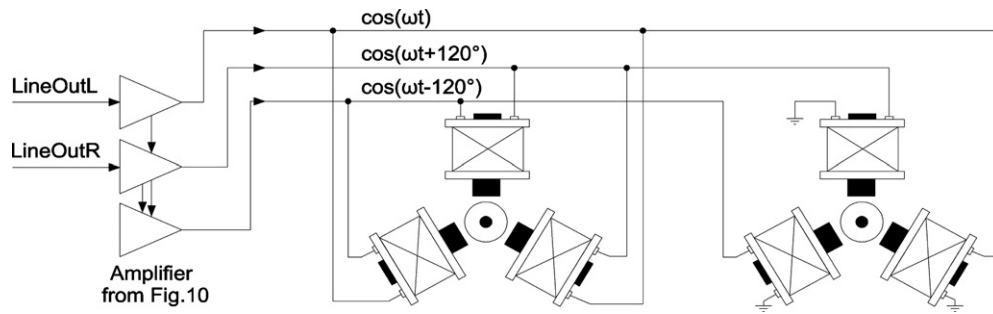


Figure 14. Electrical connection of the electromagnets: triangle (middle) or star (right); the sound card should generate 120° out-of-phase signals.

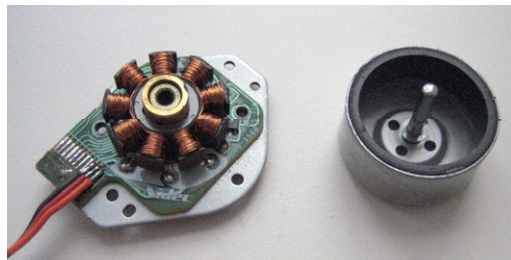


Figure 15. A small commercially available synchronous motor: a stator with electromagnets (left) and a rotor with a permanent magnet (right).

of the rotating magnetic field should first be verified using a detecting wand. Different frequencies of driving signals can be used to observe the shape and amplitude of the magnetic field, keeping in mind that the induced voltages in the wand coils are proportional to the frequency of the driving signals. The position of the optimal rotating magnetic field should again be determined, and later a compass or a suspended ring should be placed there. When a compass is used one should again start with the lower frequency of the driving signal or the compass needle might not start rotating. When a ring is used, one should start with a frequency of 50 Hz.

The three-phase driving is commonly used in contemporary 'dc motors' also. The one in figure 15 was removed from an old CD-drive of a personal computer. The rotor part is removed to see the electromagnets. There are nine electromagnets altogether, but grouped by three and internally connected in a triangle configuration. Only three wires are needed to drive the electromagnets. The rotor is equipped with a permanent magnet, which can be seen inside the metal casing. Similar motors are widely used in airplane models, and all of them can be driven by the amplifier shown in figure 9.

Small AC motors can run from a single mains phase. In such a case, two coils might be used, but the out-of-phase signal for the second coil has to be prepared from the existing signal. The simplest way is to use a capacitor in series with the second coil, as shown in figure 16. The capacitor shifts the phase of the current through the second coil enough to cause the rotation of the magnetic field within the region between both the coils. A capacitor with suitable capacitance to assure the adequate phase shift must be used. Typical values for commercially available AC single-phase, mains-driven motors are a few μF . In the case

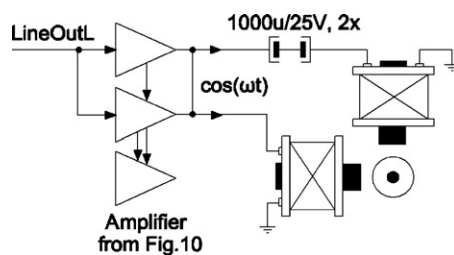


Figure 16. The out-of-phase signal for the second electromagnet can be obtained with a capacitor.

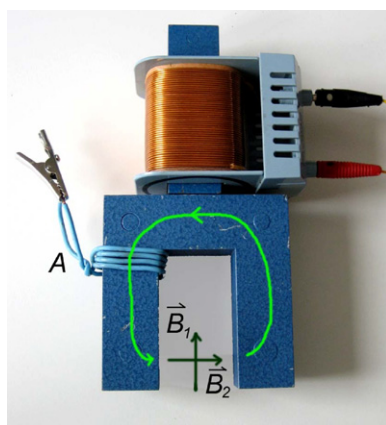


Figure 17. The U-shaped core attached to the electromagnet, a shorted coil at position A and the resulting components \vec{B}_1 and \vec{B}_2 of the rotating magnetic field.

of the described setup the driving voltages and resistances of the coils are smaller, and this also requires smaller capacitive resistance to obtain the desired phase shift. Optimal results were obtained with a capacitor of $500\ \mu\text{F}$. Such a capacitor must work with AC voltages and currents, but only electrolytic capacitors with the required capacitance are available. These are polarized and not suitable for AC, so the necessary capacitor is made by connecting two $1000\ \mu\text{F}/25\ \text{V}$ electrolytic capacitors in series. Both positive terminals are wired together, and negative terminals are used in the circuit.

The existence of the rotating magnetic field should be verified using the detecting wand, and later the compass or the suspended ring placed at the optimal position.

Some small AC single-phase motors use the technique called shaded magnetic poles and a single electromagnet to obtain the rotating magnetic field. The core of the electromagnet should be split for this purpose. The commercially available school set offers U-shaped cores suitable for the purpose (figure 17). When such a U-shaped core is attached to the core of the electromagnet, a magnetic flux from the electromagnet is split into two. There is a weak magnetic field \vec{B}_1 between the two bars, but the field has a constant direction, which can be verified using a detecting wand.

When a short-circuited coil of few turns is placed on one side of the U-shaped core at position A, an AC magnetic field caused by the electromagnet induces a voltage U_c in the coil. The induced voltage U_c is delayed for 90° with respect to the magnetic field. Since

the resistance of the wire in the coil is bigger than the inductive resistance of the same coil (about $12\text{ m}\Omega$ compared to $3\text{ m}\Omega/10\text{ }\mu\text{H}$ for this arrangement), the resulting current is almost in phase with the induced voltage U_c . This current produces magnetic field \vec{B}_2 in the gap between the two bars, the field \vec{B}_2 being orthogonal and delayed for about 90° to the field \vec{B}_1 . The combined fields \vec{B}_1 and \vec{B}_2 form a rotating magnetic field between the two bars of the U-shaped core, which can be confirmed using a detection wand, and later a compass or a suspended ring can be placed at this position to observe the rotation. The experimenter should be aware that the rotating magnetic field in this case is weak. The situation can be improved by applying a larger driving current to the electromagnet. The upper two channels of the amplifier from figure 9 can be connected in parallel to increase the current; of course, the same signal should be applied to both inputs of the amplifier as in figure 16.

6. Alternative driving for single-phase systems

For single-phase systems only, the driving current for the electromagnet can be increased by the use of the mains supply and a variable single-phase transformer. The transformer should have separated primary and secondary windings for safety. An AC ampere-meter should be connected in series with the electromagnet to monitor the current that must not exceed the maximum allowed by the electromagnet or the transformer. Another option is to use a large separation transformer (1:1, 2 kVA, no connection between the primary and secondary windings for safety), and to add a large, commercially available consumer in series with the electromagnet. Such a consumer might be a heater (1 kW at 230 VAC) or a light bulb (a bar-shaped halogen lamp with housing, 500 W at 230 VAC). All alternative driving suggestions are to be used with caution, and are not suitable for experiments involving students and hands-on work!

7. Conclusions

Tools and experiments involving the basic principles of generation, detection and utilization of a rotating magnetic field have been described. The same principles are used in contemporary AC motors, the most widely used convertors from electrical to mechanical energy. Such experiments are rarely demonstrated in secondary schools and university courses, but the use of the described simple and inexpensive tools and setups already available at schools could change the situation.

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