

Fundamental Principles of Tuning Fork Timepieces

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This article expands upon Rubens Sigelmann's article, "The Tuning Fork Era in Horology," which was published in the December 2005 BULLETIN, Vo. 47, No. 359.

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Electromagnetic Background

To understand the fundamental principles of the operation and the significance of some innovations of tuning fork timepieces, we will review some electromagnetic phenomena and their application to tuning fork timepieces. Henry Fried¹ did a remarkable review of the subject from a horological point of view. We will also review the electromagnetic phenomena, but we like to convey a sense of evolution of the knowledge of electrical phenomena. Until 600 BCE (Before the Common Era), nothing was known about electricity. In fact, the word electricity did not exist. Around 600 BCE, the Greeks discovered static electricity: by rubbing an amber bar, pieces of some other materials were attracted to it. This phenomenon was not understood until 1600 CE (the Common Era), when William Gilbert described the forces due to electricity and coined the name "electricity" (derived from the Greek word "amber") for the "thing" responsible for this behavior. Gilbert's rediscovery of electricity earned him the title of "father of modern electricity."

Not much happened in the development of electricity until Benjamin Franklin (1706-1790) found around 1750 that rubbing fur and dry cloth generated two

types of electric charges. He arbitrarily named them negative charge and positive charge. He also found that like charges repel each other, and charges of different signs attract each other. He built an electrostatic generator using the rubbing of materials.

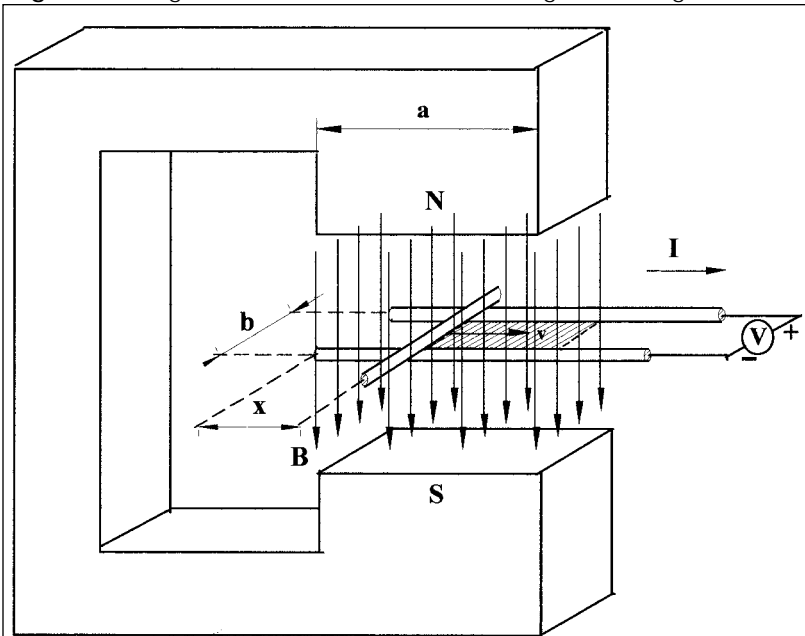
In 1785 Charles Augustin Coulomb (1736-1806) invented the torsion scale to measure the minute forces between electric charges. From his measurements he formulated the mathematical expression for the force between electrical charges. Neither Benjamin Franklin nor Coulomb knew the nature of the electric charges. The experiments of J. J. Thompson in 1897 revealed the existence of the electron, which is a fundamental particle that carries negative electric charges (labeled negative because of Franklin's arbitrary choice).

When electric charges move, and in particular in a conductor, we have an electric current. In 1820 Hans Christian Oersted (1779-1851) and Andre-Marie Ampere (1777-1851) discovered that electric current generates a magnetic field in the space around the current. How do we know that there is a magnetic field surrounding a current? Because there is "something" in that space that deflects the magnetic needle of a compass. Electric charges produce something in space called an "electric field," which exercises a force in other electric charges. Moving electric charges or currents produce something in space called a "magnetic field," which deflects the magnetic needle of a compass. What are these "somethings?" We do not know. But what we do know is that nature has behaved this way since the "Big Bang."

Oersted and Ampere demonstrated that a current generates a magnetic field. A curious question is: Could a magnetic field generate a current? Around 1831, Michael Faraday (1791-1867) and Joseph Henry (1797-1878), independently, discovered that the answer is yes. However, the answer is a little more complicated. Faraday struggled for a while with failures. He could not get a current in a circuit unless some magnetic quantity changed with time.

To understand the nature of current induction, we consider the experiment illustrated in Figure 1. The uniform magnetic field B is generated by the magnet shown in the Figure.

Figure 1. Diagram to illustrate induced voltage in a magnetic field.



The surface of each pole is a square with side **a**. The magnetic field (also called magnetic flux density or magnetic induction) is measured in *tesla* (we explain later how this unit is defined). The field is perpendicular to the plane of the two parallel conducting bars, which are separated by a distance **b**. A wire slides over these bars with a velocity **v**. A voltmeter measures the voltage induced by the motion of the wire. If there is no motion of the wire, the voltage induced is zero. The wire, a portion of the parallel bars, and the voltmeter constitute a closed electrical circuit. In this closed circuit, as Figure 1 shows, a hatched region with area **A** is crossed by the magnetic induction. We define a flux ϕ linking the closed circuit as:

$$\phi = BA$$

The flux ϕ is measured in *weber* (we explain later how this unit is defined). From Figure 1 we can see:

$$A = b(a-x)$$

However,

$$x = vt$$

where **t** is the elapsed time. Substituting the last expression in the two equations above we obtain:

$$\phi = Bb(a-vt) = Bba - Bbv t$$

The factor **Bba** obviously does not change with time; therefore, its time rate of change is zero and does not contribute to the voltage. The factor **-Bbv t** decreases with time and the time rate of change is **-Bbv**.

The voltage **V** induced in a closed circuit by a time varying field according to Faraday is given by:

$$V = -(\text{time rate of change of the flux } \phi)$$

(For those familiar with mathematics, the time rate of change of the flux is its derivative with respect to time or,

$$V = \frac{d\phi}{dt}$$

We see that in the above expressions for the voltage there is a “-” sign in front of the time rate of change. The sign comes from a consideration that is called the Lenz law (Heinrich F. E. Lenz, 1804-1865). The Lenz law is required for conservation of energy (nature requires that no energy can be created, only transformed).

To apply the Lenz law, we align the thumb of the right hand along the magnetic field and wrap the other four fingers along the direction in which the current circulates. If the flux increases with time, the current would be negative, that is, opposite to the direction given by the right-hand rule. On the other hand, if the flux decreases with the time, the current will be positive and agrees with the direction given by the right-hand rule.

The voltmeter shown in Figure 1 will read:

$$V = Bbv$$

In the scheme of Figure 1, the motion of the sliding wire causes the area linked by the flux to change; consequently a voltage is induced in the circuit. Nature requires only that the flux that links the circuit change with time to generate an induced voltage. The expression given above applies to conductors moving with velocity in a magnetic field.

Another law of nature that plays an important role in tuning fork timepieces is the force generated in a current-carrying conductor wire in a magnetic field. In Figure 2, a battery is connected to the circuit consti-

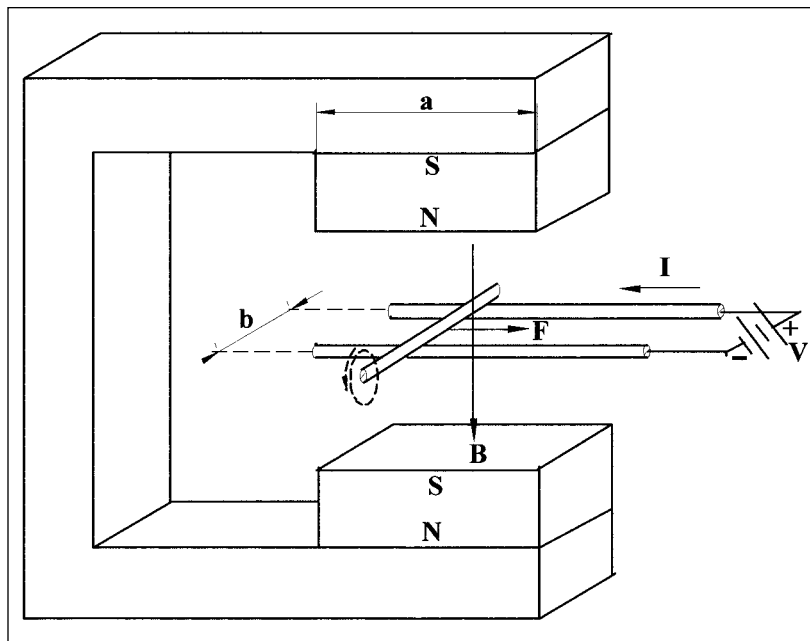


Figure 2, left. Diagram to illustrate force in a wire carrying current, in a magnetic field.

Figure 3, below. Figure to illustrate the right-hand rule to find the direction of the force due to a current in a magnetic field.



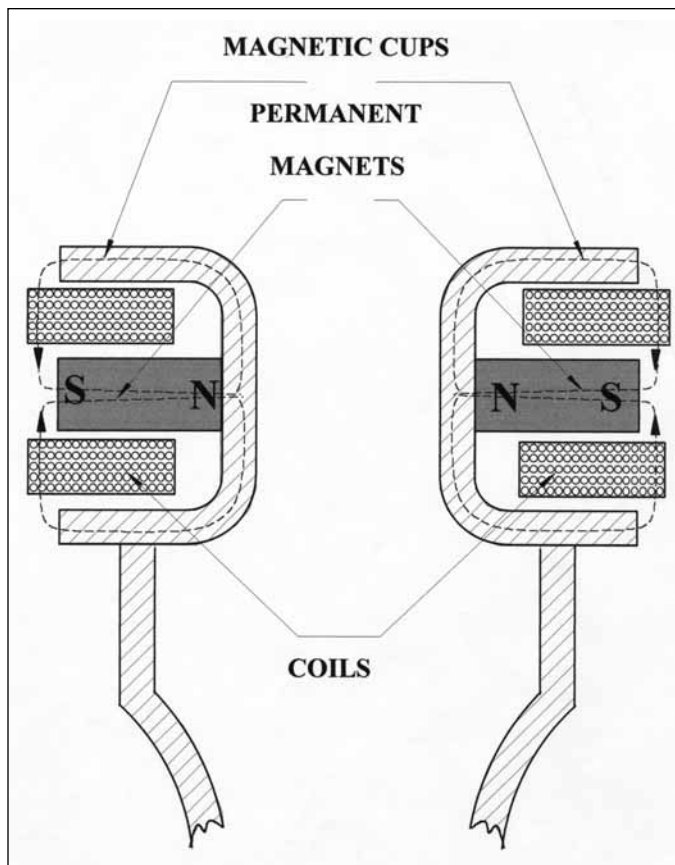


Figure 4, left. Longitudinal cut of the end of a symmetric tuning fork.

tuted by a portion of the two parallel conducting bars whose separation is b and the sliding wire. This results in a current I flowing in the circuit. Two permanent magnets are glued to a “C” magnetic structure to create a uniform magnetic induction. The two magnets, the “C” structure, and the gap constitute a magnetic circuit. The magnetic induction in the gap is now represented by a single arrow B . As a result of the current flowing through the sliding bar in the magnetic field, such a bar is subject to a force F whose value is given by:

$$F = bIB$$

and whose direction is given by the right-hand rule illustrated in Figure 3. The thumb points to the current, the forefinger, the magnetic induction, and the middle finger give the direction of the force. Figure 2 shows the magnetic field as a dotted line and its direction around the sliding wire. The magnetic field of the wire adds to the magnetic uniform field to the left side of the wire, whereas it subtracts to the right side of the wire. Note also in Figure 1 the current direction causes a force opposite to the direction of the velocity. This means that in order to keep the sliding bar moving with the velocity v , we must apply a force opposite to the force due to the current (consistent with Lenz law).

Suppose that we apply force on the surface of a table. The laws of nature require that the table apply a force against our hand. This is called the principle of action and reaction. This principle applies to the force due to a

current in a magnetic field. Due to the reaction principle, a force of opposite direction to the force applied to the wire is applied to the “C” structure and the two permanent magnets.

We now discuss the definitions of the units used in magnetism. The unit of magnetic induction or flux density is *tesla* (T) and can be defined using the equation:

$$F = bIB.$$

If a current $I=1$ ampere flows in wire $b=1$ meter long perpendicular to the magnetic field and the resultant force $F=1$ newton, then the induction or flux density B is 1 tesla. The flux density of the earth is 5×10^{-5} tesla. The maximum induction in the iron of magnetic devices is of the order of 1 tesla.

The unit of magnetic flux is *weber* (Wb) and it can be defined from the equation:

$$\phi = BA$$

if the magnetic induction $B=1$ tesla and the area of a closed circuit is $A=1$ square meter, then the flux is 1 weber.

Fundamental Principles of Tuning Fork Timepiece Functioning

We reviewed the principles of electromagnetics that are applied to tuning fork timepieces. Now we will show how these principles are implemented in a tuning fork watch. Figures 4 and 5 show sketches of the ends of the two types of tuning forks used in watches. Figure 4 represents a longitudinal cut of the ends of a symmetric tuning fork. The material used to make the permanent magnets is Alnico. As we see later, this has significant implications on improving tuning fork watches. The watches that use this end are Accutron Models 214, 218, 220, 224, ESA 9162, Citizen Hisonic. The tuning forks of the Accutron 219 and the Citizen Cosmotron are not symmetric. Only one side of the tuning fork has a coil. The other side is a dummy end. In Figure 4 the dotted closed loops represent one line of magnetic field generated by the permanent magnets. For simplicity we represent only four lines. There are several of these loops concentric with the loop represented in Figure 4. The little circles represent the cross section of the copper wire of the coil. The coils are fixed to the frame of the watch. We assume also that the direction of the current in the left side coil is such that the current flows out of the top cross-section and into the bottom cross-section. We apply the right-hand rule to find that the direction of the force acting upon the coil (Figure 3) is from the left to the right and the force applied to the cup, right to the left. The direction of the force applied to the right cup must be from the left to the right. That means that the current in the right coil must be inverted with respect to the current in the left coil. The elec-

tronic circuit maintains the oscillation of the tuning fork by applying pulses of current at the same frequency of the tuning fork.

In 1966, Dr. Karl Strnat, U.S. Air Force Materials Laboratory, Wright-Patterson Air Force Base, discovered that the addition of some rare earth substances to certain ceramic materials improved the magnetic properties of permanent magnets dramatically. He developed a Samarium-Cobalt compound (SmCo5) that was at least four times stronger than Alnico V. Very rapidly, Dr. Strnat and other researchers found other proportions and other substances that further increased the strength of permanent magnets. Around the 1970s permanent magnets were more than 10 times stronger than Alnico V. This had an enormous impact on the development of newer tuning fork watches. Increasing the frequency of the tuning fork would result in watches with higher accuracy. However, the trade-off was that the losses would increase with the square of the frequency. The advent of these very powerful permanent magnets permitted the magnetic field density B to increase significantly. Thus, according to the formula $F = bIB$, we may decrease the current by the amount of increase of the magnetic field density and achieve the same force. The reduction of the current results in reduction of losses. The use of stronger ceramic permanent magnets allowed to circumvent the problem of increase of losses with higher frequencies. A topological arrangement of the coil and permanent magnets are shown in Figure 5. For clarity, the coil is shown outside the gap between the ceramic magnets. In reality the coil should be inside the gap, as suggested by the arrow in the figure. Four thin slab ceramic magnets are glued to the iron cups. In this view, the cups hide the two top magnets. The direction of the magnetic field is shown by four vertical arrows. This arrangement not only simplifies the manufacture of the watch (a single coil that does not require a spool), but also improves the distribution of magnetic field in the gap. This type of

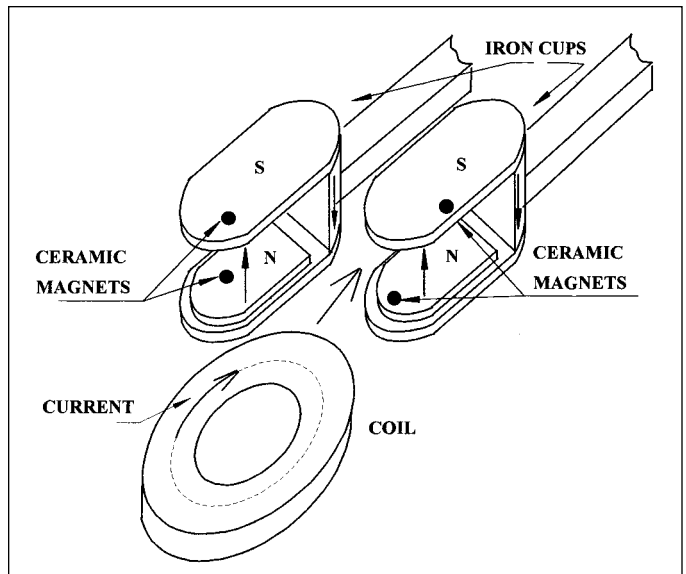


Figure 5, above. The end of a type of coil and tuning fork arrangement.

arrangement is used in the following watches: Accutron 230, Swissonic and Omega Megasonic f720. The frequency of the Accutron 230 and Swissonic is 480 Hz. The frequency of the Megasonic f720 is 720 Hz.

Note

1. Henry B. Fried, *The Electric Watch Repair Manual*, 2nd Edition (B. Jadow & Sons, 1972): pp. 1-34.

About the Author

Rubens A. Sigelmann retired from teaching in the Electrical Engineering Department at the University of Washington, Seattle, after 35 years. He joined the NAWCC in 1976 and is a past president of Chapter 50. He also gave several talks to chapters and regionals. Rubens obtained his training and inspiration in watch and clockmaking from the late George Lewis. George was the leader in horological education at the North Seattle Community College for many years.