Quantum Mechanics_Eddy currents

Eddy currents (also called **Foucault currents**[1]) are electric currents induced within conductors by a changing Magnetic field in the conductor. These circulating eddies of current have Inductance and thus induce magnetic fields. These fields can cause repulsion, attraction,[2] propulsion, drag, and heating effects. The stronger the applied magnetic field, the greater the electrical conductivity of the conductor, and the faster the field changes, the greater the currents that are developed and the greater the fields produced.

Origin of term

The term *eddy current* comes from analogous currents seen in water when dragging an oar breadthwise: localised areas of turbulence known as *eddies* give rise to persistent vortices. Somewhat analogously, eddy currents can take time to build up and can persist for very short times in conductors due to their inductance.

History

The first person to observe current eddies was François Arago (1786–1853), the 25th Prime Minister of France, who was also a mathematician, physicist and astronomer. In 1824 he observed what has been called rotatory magnetism, and that most conductive bodies could be magnetized; these discoveries were completed and explained by Michael Faraday (1791–1867).

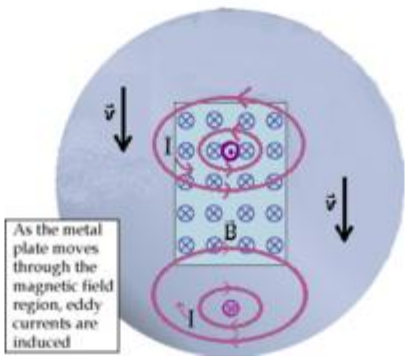
In 1834, Heinrich Lenz stated Lenz's law, which says that the direction of induced current flow in an object will be such that its magnetic field will oppose the magnetic field that caused the current flow. Eddy currents produce a secondary field that cancels a part of the external field and causes some of the external flux to avoid the conductor.

French physicist Léon Foucault (1819–1868) is credited with having discovered eddy currents. In September, 1855, he discovered that the force required for the rotation of a copper disc becomes greater when it is made to rotate with its rim between the poles of a magnet, the disc at the same time becoming heated by the eddy current induced in the metal. The first use of eddy current for non-destructive testing occurred in 1879 when David E. Hughes used the principles to conduct metallurgical sorting tests.[3]

Explanation

Eddy currents in conductors of non-zero resistivity generate heat as well as electromagnetic forces. The heat can be used for induction heating. The electromagnetic forces can be used for levitation, creating movement, or to give a strong braking effect. Eddy currents can also have undesirable effects, for instance power loss in transformers. In this application, they are minimized with thin plates, by lamination of conductors or other details of conductor shape.

Self-induced eddy currents are responsible for the skin effect in conductors.[4]The latter can be used for non-destructive testing of materials for geometry features, like micro-cracks.[5] A similar effect is the proximity effect, which is caused by externally induced eddy currents.[6]



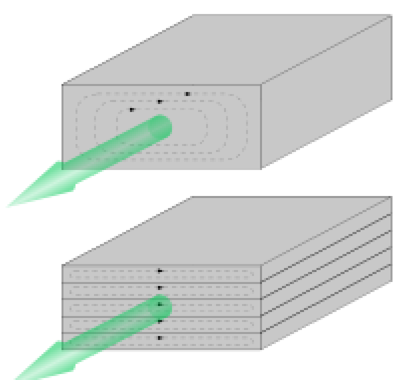
As the circular plate moves down through a small region of constant magnetic field directed into the page, eddy currents are induced in the plate. The direction of those currents is given by Lenz's law, i.e. so that the plate's movement is hindered.

When a conductor moves through an inhomogeneous field generated by a source,electromotive forces (EMFs) can be generated around loops within the conductor. These EMFs acting on the resistivity of the material generate a current around the loop, in accordance with Faraday's law of induction. These currents dissipate energy, and create a magnetic field that tends to oppose changes in the current- they have inductance.

Eddy currents are created when a conductor experiences changes in the magnetic field. If either the conductor is moving through a steady magnetic field, or the magnetic field is changing around a stationary conductor, eddy currents will occur in the conductor. Both effects are present when a conductor moves through a varying magnetic field, as is the case at the top and bottom edges of the magnetized region shown in the diagram. Eddy currents will be generated wherever a conducting object experiences a change in the intensity or direction of the magnetic field at any point within it, and not just at the boundaries.

The swirling current set up in the conductor is due to electrons experiencing aLorentz force that is perpendicular to their motion. Hence, they veer to their right, or left, depending on the direction of the applied field and whether the strength of the field is increasing or declining. The resistivity of the conductor acts to damp the amplitude of the eddy currents, as well as straighten their paths.Lenz's law states that the current swirls in such a way as to create an induced magnetic field that opposes the phenomenon that created it. In the case of a varying applied field, the induced field will always be in the opposite direction to that applied. The same will be true when a varying external field is increasing in strength. However, when a varying field is falling in strength, the induced field will be in the same direction as that originally applied, in order to oppose the decline.

An object or part of an object experiences steady field intensity and direction where there is still relative motion of the field and the object (for example in the center of the field in the diagram), or unsteady fields where the currents cannot circulate due to the geometry of the conductor. In these situations charges collect on or within the object and these charges then produce static electric potentials that oppose any further current. Currents may be initially associated with the creation of static potentials, but these may be transitory and small.



Lamination of conductors parallel to the field lines reduce eddy currents

Eddy currents generate resistive losses that transform some forms of energy, such as kinetic energy, into heat. This Joule heating reduces efficiency of iron-coretransformers and electric motors and other devices that use changing magnetic fields. Eddy currents are minimized in these devices by selecting magnetic corematerials that have low electrical conductivity (e.g., ferrites) or by using thin sheets of magnetic material, known as laminations. Electrons cannot cross the insulating gap between the laminations and so are unable to circulate on wide arcs. Charges gather at the lamination boundaries, in a process analogous to theHall effect, producing electric fields that oppose any further accumulation of charge and hence suppressing the eddy currents. The shorter the distance between adjacent laminations (i.e., the greater the number of laminations per unit area, perpendicular to the applied field), the greater the suppression of eddy currents.

The conversion of input energy to heat is not always undesirable, however, as there are some practical applications. One is in the brakes of some trains known aseddy current brakes. During braking, the metal wheels are exposed to a magnetic field from an electromagnet, generating eddy currents in the wheels. The eddy currents meet resistance as charges flow through the metal, thus dissipating energy as heat, and this acts to slow the wheels down. The faster the wheels are spinning, the stronger the effect, meaning that as the train slows the braking force is reduced, producing a smooth stopping motion. induction heating makes use of eddy currents to provide heating of metal objects.

Power dissipation of eddy currents

Under certain assumptions (uniform material, uniform magnetic field, no skin effect, etc.) the power lost due to eddy currents per unit mass for a thin sheet or wire can be calculated from the following equation:[7]

$$P = \frac{\pi^2 B_\text{p}^2 d^2 f^2}{6k\rho D},$$

where

- P is the power lost per unit mass (W/kg),
- B_p is the peak magnetic field (T),
- d is the thickness of the sheet or diameter of the wire (m),
- f is the frequency (Hz),
- k is a constant equal to 1 for a thin sheet and 2 for a thin wire,
- ρ is the resistivity of the material (Ω m), and
- D is the density of the material (kg/m^3).

This equation is valid only under the so-called quasi-static conditions, where the frequency of magnetisation does not result in the skin effect; that is, the electromagnetic wave fully penetrates the material.

Skin effect

Main article: skin effect

In very fast-changing fields, the magnetic field does not penetrate completely into the interior of the material. This *skin effect* renders the above equation invalid. However, in any case increased frequency of the same value of field will always increase eddy currents, even with non-uniform field penetration.[*citation needed*]

The penetration depth for a good conductor can be calculated from the following equation:[8]

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}},$$

where δ is the penetration depth (m), *f* is the frequency (Hz), μ is the magnetic permeability of the material (H/m), and σ is the electrical conductivity of the material (S/m).

Diffusion equation

The derivation of a useful equation for modelling the effect of eddy currents in a material starts with the differential, magnetostatic form of Ampère's law,[9]providing an expression for the magnetizing field **H** surrounding a current density **J**:

$$\nabla \times \mathbf{H} = \mathbf{J}.$$

Taking the curl on both sides of this equation and then using a common vector calculus identity for the curl of the curl results in

$$\nabla \left(\nabla \cdot \mathbf{H}\right) - \nabla^2 \mathbf{H} = \nabla \times \mathbf{J}.$$

From Gauss's law for magnetism, $\nabla \cdot \mathbf{H} = 0$, so

$$-\nabla^2 \mathbf{H} = \nabla \times \mathbf{J}.$$

Using Ohm's law, $\mathbf{J} = \sigma \mathbf{E}$, which relates current density **J** to electric field **E** in terms of a material's conductivity σ, and assuming isotropic homogeneous conductivity, the equation can be written as

$$-\nabla^2 \mathbf{H} = \sigma \nabla \times \boldsymbol{E}.$$

Using the differential form of Faraday's law, $\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$, this gives

$$\nabla^2 \mathbf{H} = \sigma \frac{\partial \mathbf{B}}{\partial t}.$$

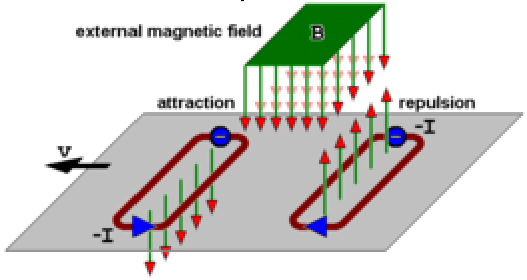
By definition, $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, where **M** is the Magnetization of the material and μ_0 is the vacuum permeability. The diffusion equation therefore is

$$\nabla^2 \mathbf{H} = \mu_0 \sigma \left(\frac{\partial \mathbf{M}}{\partial t} + \frac{\partial \mathbf{H}}{\partial t} \right).$$

Applications

Electromagnetic braking

Main article: Eddy current brake

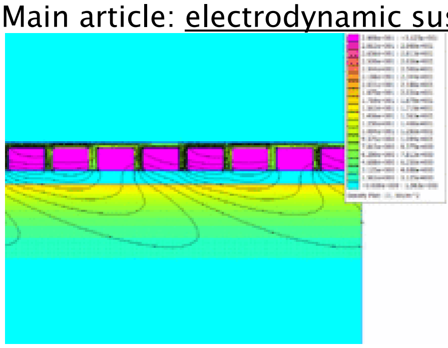


Braking forces resulting from eddy currents in a metal plate moving through an external magnetic field

Eddy currents are used for braking; since there is no contact with a brake shoe or drum, there is no mechanical wear. However, an eddy current brake cannot provide a "holding" torque and so may be used in combination with mechanical brakes, for example, on overhead cranes. Another application is on some roller coasters, where heavy copper plates extending from the car are moved between pairs of very strong permanent magnets. Electrical resistance within the plates causes a dragging effect analogous to friction, which dissipates the kinetic energy of the car. The same technique is used in electromagnetic brakes in railroad cars and to quickly stop the blades in power tools such as circular saws. Using electromagnets, the strength of the magnetic field can be adjusted and so the magnitude of braking effect changed.

Repulsive effects and levitation

Main article: electrodynamic suspension



A cross section through a linear motor placed above a thick aluminium slab. As the linear induction motor's field pattern sweeps to the left, eddy currents are left behind in the metal and this causes the field lines to lean.

In a varying magnetic field the induced currents exhibit diamagnetic-like repulsion effects. A conductive object will experience a repulsion force. This can lift objects against gravity, though with continual power input to replace the energy dissipated by the eddy currents. An example application is separation ofaluminum cans from other metals in an eddy current separator). Ferrous metals cling to the magnet, and aluminum (and other non-ferrous conductors) are forced away from the magnet; this can separate a waste stream into ferrous and non-ferrous scrap metal.

With a very strong handheld magnet, such as those made from neodymium, one can easily observe a very similar effect by rapidly sweeping the magnet over a coin with only a small separation. Depending on the strength of the magnet, identity of the coin, and separation between the magnet and coin, one may induce the coin to be pushed slightly ahead of the magnet - even if the coin contains no magnetic elements, such as the US penny. Another example involves dropping a strong magnet down a tube of copper[10] - the magnet falls at a dramatically slow pace.

Perfect conductors allow lossless conduction that allows eddy currents to form on the surface of the conductor that exactly cancel any changes in the magnetic field applied to the object after the material's resistance went to zero, thus allowingmagnetic levitation. Superconductors are a subclass of perfect conductors in that they also exhibit the Meissner Effect, an inherently quantum mechanical phenomenon that is responsible for expelling any magnetic field lines present during the superconducting transition, thus making the magnetic field zero in the bulk of the superconductor.

Attractive effects

In some geometries the overall force of eddy currents can be attractive, for example, where the flux lines are past 90 degrees to a surface, the induced currents in a nearby conductor cause a force that pushes a conductor towards an electromagnet.[2]

Identification of metals

In coin operated vending machines, eddy currents are used to detect counterfeit coins, or slugs. The coin rolls past a stationary magnet, and eddy currents slow its speed. The strength of the eddy currents, and thus the retardation, depends on the conductivity of the coin's metal. Slugs are slowed to a different degree than genuine coins, and this is used to send them into the rejection slot.

Vibration and position Sensing

Eddy currents are used in certain types of proximity sensors to observe the vibration and position of rotating shafts within their bearings. This technology was originally pioneered in the 1930s by researchers at General Electric using vacuum tube circuitry. In the late 1950s, solid-state versions were developed byDonald E. Bently at Bently

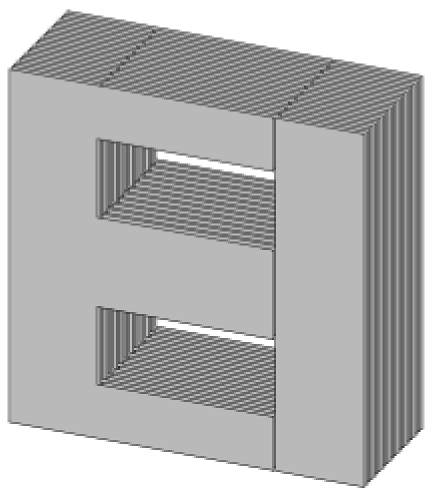
Nevada Corporation. These sensors are extremely sensitive to very small displacements making them well suited to observe the minute vibrations (on the order of several thousandths of an inch) in modernturbomachinery. A typical proximity sensor used for vibration monitoring has a scale factor of 200 mV/mil. Widespread use of such sensors in turbomachinery has led to development of industry standards that prescribe their use and application. Examples of such standards are American Petroleum Institute (API) Standard 670 and ISO 7919.

Structural testing

Eddy current techniques are commonly used for the nondestructive examination(NDE) and condition monitoring of a large variety of metallic structures, includingheat exchanger tubes, aircraft fuselage, and aircraft structural components..

Side effects

Eddy currents are the root cause of the skin effect in conductors carrying AC current.



Lamination of magnetic cores in transformers greatly improves the efficiency by minimising eddy currents

Similarly, in magnetic materials of finite conductivity eddy currents cause the confinement of the majority of the magnetic fields to only a couple skin depths of the surface of the material. This effect limits the flux linkage in inductors andtransformers having magnetic cores.

Other applications

- Metal detectors
- Conductivity meters for non-magnetic metals[11][12]
- Eddy current adjustable-speed drives

- Eddy-current testing
- Electric meters (Electromechanical Induction Meters)
- induction heating
- Proximity sensor (Displacement sensors)
- vending machines (detection of coins)
- Coating Thickness Measurements [13]
- Sheet Resistance Measurement [14]
- eddy current separator for metal separation [15]
- Mechanical speedometers
- Safety Hazard and defect detection applications

References

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