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Nicola Bowler

Eddy-Current Nondestructive Evaluation

Springer

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It is exciting and profound that mathematical physics can be used to calculate quantities of practical interest, that have a real impact on society in the context of inspections of aircraft, vehicles, bridges, nuclear power plants and other structures whose integrity is critical to human and environmental safety.

Excerpt from Chap. 5.

Dedicated to all those who have encouraged and inspired me, and especially to John, whose commitment to the truth drew me in.

Preface

This book is intended for senior undergraduate and graduate engineers and scientists, who need a deeper understanding of eddy-current nondestructive evaluation (EC NDE) that can be found in a guide for practitioners. It is written from the standpoint that despite powerful advances in computational electromagnetics, it is important to comprehend the physical principles at work in order to fully master methods of NDE. This book accompanies a course of the same name that has been developed at Iowa State University through support from the Center for Nondestructive Evaluation, and it is also intended to provide a reference and learning aid for nondestructive testing (NDT) engineers in industry and government laboratories.

Theoretical concepts from electricity and magnetism are used freely throughout this text and I am conscious of the fact that many professional test engineers have not taken senior-level courses in electromagnetics or may need to be reminded of the principles. When concepts, laws, and relationships are introduced in the text, I have tried to provide sufficient supporting explanation to aid those of you who may be meeting these for the first time.

The practice of eddy-current nondestructive testing grew, from the middle part of the twentieth century, following the vital impetus and pioneering achievements of Friedrich Förster and his colleagues. Förster laid foundations on which others have built. In the early years, eddy-current methods were used for metal sorting, hardness measurements, and the evaluation of heat treatments, detected through sensing electrical resistivity variations in the samples. These applications were followed quickly by the detection of cracks and corrosion. From the very beginning of these developments, it has been recognized that the introduction of new techniques, the improvement of existing methods, and the interpretation of measurements can benefit greatly from an understanding of the fundamental behavior of the electromagnetic fields. The aim of this book is to bring a knowledge of these fundamentals to new generations of engineers and scientists.

Eddy-current nondestructive evaluation is a commonly practiced method of electromagnetic NDT. The method has been a workhorse of metals characterization and defect detection for many decades, operating at frequencies typically ranging from a few kiloHertz to a few megaHertz. One survey estimated that the method is used in 10% of all NDT inspections. Other electromagnetic approaches, in particular, those that employ higher operating frequencies, are growing in usage in accordance with the expanding use of nonmetallic structural materials such as fiber-based composites. In this text, the discussion is limited to operating frequencies of the order of megaHertz and below, which means that microwave and teraHertz NDT, and magneto-optic imaging, remain outside the scope of this book.

My writing has been guided by four concepts. The work is intended to be visually appealing, with plenty of diagrams to aid comprehension (thanks go to: John Bowler, Adam Cich, Danielle Kimler, Ryan Williams, John Graham, Yi Lu, and Amin Gorji who have all contributed illustrations to this work). I have attempted to place the reported developments in the field of electromagnetic NDT in historical context, and I have tried to maintain a high level of clarity and transparency in the work by including many supporting references. A number of "back-of-the-envelope" example calculations and exercises are included. These are simple calculations that can be done by hand and impart a working knowledge of the connection between electromagnetic theory and the practical measurements described.

The text begins with a brief history of the development of eddy-current NDT, followed by introductions to electromagnetic induction and the basic process of eddy-current NDT, Chap. 1. In Chap. 2, the concept of the electromagnetic field is introduced, and the relationship between electric current and the magnetic field is described qualitatively in the context of an air-cored eddy-current coil near an unflawed metal test-piece. The skin effect and material parameters which affect it are discussed.

The influence of ferromagnetism on eddy-current inspection is profound. For the successful inspection of most steels or other types of ferromagnetic conductor, an understanding of the magnetization (and demagnetization) process is important. Chapter 3 provides an introduction to the process of magnetization in ferromagnetic materials and the meaning of permeability is explained.

The observed quantity in eddy-current NDT is the electrical impedance of the probe coil. Proper interpretation of the impedance allows the inspector to infer material property information, and to detect and characterize defects. Chapter 4 provides an introductory description of circuit theory that is relevant to EC NDE. Different contributions to the probe coil impedance are discussed. Continuing to build the background knowledge needed to more completely describe the electromagnetic behavior of a probe coil, and to become equipped to interpret the measured impedance, Chap. 5 describes the formation and various expressions of Maxwell's equations, from which the equations governing the electromagnetic fields can be formed. Further, expressions of interface conditions on the electromagnetic field are provided. The interface conditions are needed, along with the governing equations, to solve for the fields generated by eddy-current probe coils. They also provide the mathematical tools by which the influence on the impedance of the test-piece can be accounted for.

In Chap. 6, the many background elements considered in earlier chapters come together to allow a detailed illumination of the ways in which various factors affect the measured impedance of an eddy-current probe coil. This chapter embodies the core knowledge of eddy-current NDE insofar as detailing the response of an eddy-current probe to an unflawed test-piece of relatively simple shape. The effect of probe factors such as coil dimensions, construction with or without a ferrite core, and frequency of excitation current are considered. Test-piece factors conductivity, permeability, shape, and position relative to the coil are discussed. In particular, Chap. 6 initially conveys how to compute and interpret the impedance of a coil that is isolated from any test-piece and then introduces the effect of certain canonical test-piece geometries: e.g., the case of a surface coil positioned above a half-space conductor (i.e., a thick, flat conductor) and of a coil encircling a solid, circular–cylindrical rod. For the surface coil, the role of the ferrite core in enhancing inspections is described, along with sources of uncertainty in inspections due to, for example, unknown variations in the coil windings or accidental tilt of the probe during an inspection. The impedance plane diagram is introduced in absolute and normalized forms.

The inspection of test-pieces with more complex geometry, such as layered plates or tubes, is discussed in Chap. 7. The discussion includes the description of impedance plane diagrams for surface coils, encircling coils, and bobbin coils in relation to these test-pieces. The effect of the test-piece edge on the measured probe coil impedance is also described.

In Chap. 8, various probe configurations are discussed in the context of particular applications for which they are well suited. Common and more exotic configurations are included. Practically speaking, probes are often composed of more than one coil either for differential operation that is particularly effective in defect detection or so that each coil may be individually optimized for its role as drive or pick up coil. Some probes are of hybrid design, in which a drive coil induces eddy currents in the test-piece yet the signal is measured by another type of sensor, e.g., a Hall device or a giant magnetoresistive (GMR) sensor. Thin, flexible coils designed for in situ structural health monitoring, and array probes designed for rapid wide-area inspection, are also presented.

Having laid groundwork giving a detailed description of impedance signals due to *un*flawed test-pieces in prior chapters, attention is turned to the effect of defects on the impedance of an eddy-current probe coil, in Chap. 9. In keeping with the approach of this text, simple flaw shapes are considered with the intent of imparting comprehension of how the various characteristics of a defect (its size, shape, location, filler material, etc) influence the observed change in impedance of the eddy-current coil as it approaches the defect. Two regimes are considered: the "small flaw" regime, when the flaw is significantly smaller than the electromagnetic skin depth in the material, and the "thin-skin" regime, when a surface crack is significantly deeper than the electromagnetic skin depth. In these regimes, analytical solutions for the impedance change due to the defect can be derived and give a clear insight into the way in which the coil impedance changes in the presence of these and similar flaws.

Reflecting on a decade of university-based teaching in the field of NDE, and on decades-long conversations with industrial engineers responsible for NDT operations in aerospace, energy, and infrastructure engineering sectors, it is my view that the industrial need for well-educated NDT engineers remains strong. I offer this text to the NDT community in the hope that it will be useful in educating many NDT professionals now and for years to come. I extend my gratitude to Steve Burke and Buzz Wincheski for their comments on various parts of this text.

Ames, IA, USA Nicola Bowler

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Chapter 1
Introduction

Abstract This opening chapter begins with a brief history of the development of the field of eddy-current (EC) nondestructive evaluation (NDE), beginning with Faraday's discovery of the law of electromagnetic induction and including contributions of Henry, Hughes, and Förster. The role of the law of electromagnetic induction in EC NDE is described qualitatively and the principles via which a material defect may be detected are discussed. Finally, the parameters by which a simple EC surface coil may be described are introduced.

1.1 Introduction

A study conducted by the Institute of Metals [1] discovered that eddy-current nondestructive evaluation (EC NDE) accounts for approximately ten percent of NDE inspections. Other methods in common usage include inherently "visual" inspection methods such as liquid penetrant and magnetic particle testing (50%), ultrasonic, and X-ray methods (approximately 35%). The optimum method for a particular inspection depends on the nature of the specimen under test, and also on the information that is sought. Overviews of some of these methods can be found in [1, 2], but the primary focus of this text is eddy-current NDE.

Eddy-current NDE relies on the induction of electrical current in the part being tested. For this reason, it is used for the inspection of *metals*. Eddy-current NDE is useful for the determination of certain material properties and detection and characterization of inhomogeneities in metals. The method is fundamentally related to the electromagnetic properties of a test-piece. For this reason, it is commonly applied in metal sorting and identification, based on measurement of the metal conductivity, and in detection and characterization of defects in metal parts. These defects may be cracks, pits, dents, scratches, corrosion, heat-affected zones, and others. They may appear at the surface or below the surface. They are found in aerospace structures, nuclear power plant components, railroad tracks, pipelines, sheet metal, rods, and bars, to name a few.

Much early work in the field was done by Friedrich Förster [3], who developed practical eddy-current NDE techniques for many different test geometries, and also

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developed the theory and physics of the practice. The company he founded (Foerster Instruments, Inc.) is still a leading producer of eddy-current test instruments.

1.2 Historical Background

1.2.1 Michael Faraday

Michael Faraday (1791–1867, Fig. 1.1) was an English physicist and chemist. He came from a poor background and was largely self-educated. In 1821, he discovered the phenomenon of electromagnetic induction, which is one of the most far-reaching scientific discoveries of all time [5]. Like many other scholars of his time, Faraday was fascinated by the experiment of Hans Oersted in 1819 in which it was demonstrated that a compass needle could be deflected if brought near to a wire through which electric current was passing. Faraday set out to show, conversely, that electric current could be produced by a magnetic field. Faraday wound a coil of wire, connected to a battery, around one segment of an iron ring (circuit A in Fig. 1.2). An electric current could be made to pass through the wire by closing a switch. Another coil of wire was wound around a different segment of the iron ring (circuit B). On closing the switch in circuit A, a magnetic field was set up by the current flowing in coil A, magnetizing the iron ring. The magnetic field was concentrated in the high permeability iron, which acts as a magnetic circuit conveying the magnetic field to circuit B. The magnetic field created in the iron ring by coil A then coupled with coil B and induced a current to flow in circuit B. This secondary induced current was detected by deflection of the galvanometer. In this experiment, Faraday had invented the first transformer. His original ring is shown in Fig. 1.3.

Fig. 1.1 Michael Faraday, English physicist and chemist, 1791–1867 [4]

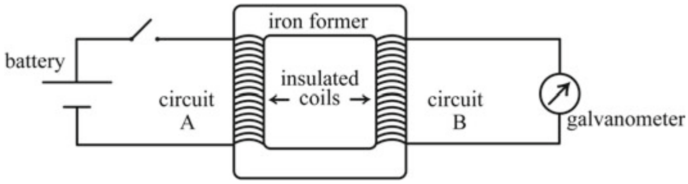

Fig. 1.2 Schematic diagram of Faraday's transformer

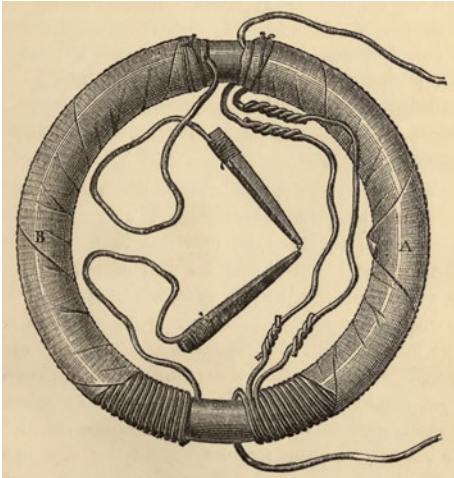

Fig. 1.3 Faraday's transformer [6]

One aspect of his experiment took Faraday by surprise. Rather than a steady flow of current in circuit B, as Faraday had expected, there was a transient current in response to the closing of the switch in circuit A, and another transient current in the opposite direction when the circuit was broken. In between, while the current was flowing steadily in circuit A, no current flowed in circuit B. To explain this, Faraday visualized magnetic field lines that sprang outward from coil A when the switch was closed and collapsed again as the circuit was broken. He hypothesized that electric current was induced in a conductor only when magnetic field lines moved across it. We now know that magnetic fields that vary in time and/or space are capable of inducing electric current flow in a nearby conductor.

Faraday continued to carry out significant experiments in electricity, inventing the first electric generator in 1831, probably the single greatest electrical discovery in history. He was also a tremendously popular lecturer in science for the general public, his lecturers being attended even by royalty and novelists of the time. Faraday lends his name to a unit measuring the quantity of electricity (1 Faraday ≡ 96,500 C) and to the unit of electrostatic capacitance, the Farad (F), named in his honor.

Fig. 1.4 Joseph Henry, American physicist, 1797–1878 [7]

1.2.2 Joseph Henry

A contemporary of Faraday, Joseph Henry (1797–1878, Fig. 1.4) was an American physicist who discovered the phenomenon of electromagnetic induction in 1820, before Faraday, but was unable to complete his experiments and publish his results in advance of Faraday due to a heavy teaching load. For this reason, Faraday receives the credit for the discovery [5]. In Henry's paper, however, he explained that the electric current in a coil can induce another current not only in another coil but in itself—the first description of the phenomenon of self-induction. The current observed in any coil is, therefore, a combination of the original current and the induced current. Joseph Henry made many further significant contributions to scientific and engineering advancement, especially in his role as the first secretary of the Smithsonian Institution, through which he encouraged worldwide communication of scientific discoveries. Upon his death, it was agreed that the unit of inductance should be named the Henry, in his honor.

1.2.3 David Hughes

Following the discovery of electromagnetic induction, nearly 50 years elapsed before further experiments suggested a path toward practical application of the phenomenon in materials testing. David Edward Hughes (1831–1900) was a Welsh experimental scientist and accomplished musician. He conducted some important experiments of relevance to EC NDE in 1879, when he showed that the properties of a current-carrying coil changed when the coil was placed in contact with metals of different conductivity and permeability. Here, lies the foundation for identification of metals and alloys by eddy-current testing, to be discussed in Chaps. 6 and 8.

1.2.4 Friedrich Förster

Following the work of Hughes, another 54 years passed before eddy-current technology was developed for industrial application. While working for the Kaiser Wilhelm Institute in Germany, 1933, Prof. Friedrich Förster played a very important role in adapting eddy-current technology for industrial use. He developed instruments for measuring conductivity and for sorting mixed ferrous components, among others, and contributed significantly to the understanding and interpretation of eddy-current signals, introducing the so-called "Förster diagram", which is related to the impedance-plane plots that will be described in this work. As mentioned above, Förster founded his own company (Foerster Instruments, Inc.) in 1948, a company whose business is based on eddy-current testing.

Many advances in the development of EC NDE were made in the 1950s and 1960s, in particular in the context of aviation and nuclear power industries. EC NDE is now a widely used and well-understood inspection technique for flaw detection and characterization as well as for materials property characterization. The development of EC NDE continues to be an active area of research in the present era. Research encompasses the design and realization of specialized probes for ever-more-challenging inspections, often assisted by computational modeling of the probe and its environment. Present-day research also focuses upon improving the interpretation of noisy signals, often with the goal of increasing inspection speed. Generally speaking, EC NDE plays an important role in improving safety, quality, and efficiency in aviation, transportation, infrastructure, and energy sectors.

1.3 Electromagnetic Induction

What happens when a time-varying electric current passes through a simple loop of wire held near a conductor such as a metal plate? As shown schematically in Fig. 1.5, the time-varying current flowing in the wire loop has the effect (somehow) of producing (actually, *inducing*) an electric current which flows in the metal plate. The current in the plate in some sense mirrors the applied current flowing in the wire loop, but flows in the opposite direction. These induced currents are known as eddy currents. The term "eddy current" was coined due to the analogy between vortex currents (eddies) in laminar fluid flow and the flow of these induced, circulating, electrical currents. In practice, eddy currents always flow in closed paths.

How are eddy currents induced? The answer lies in the phenomenon of electromagnetic induction, first observed experimentally by Faraday, who hypothesized the existence of the electric and magnetic fields in order to explain his observations.

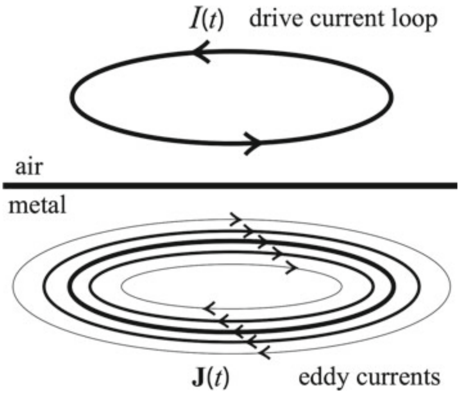

Fig. 1.5 Eddy currents induced in a metal part by a time-varying current loop in air. The eddy-current density in the conductor, $\mathbf{J}(t)$, is a vector field that is described in detail in Sect. 2.2

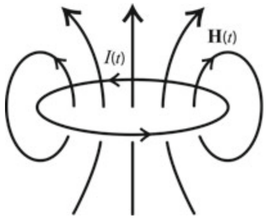

Fig. 1.6 Magnetic field associated with a time-varying current loop in air

The fact that the applied current is varying means that a magnetic field, denoted **H** with units Ampères per meter (A/m), is produced in the vicinity of the current loop, Fig. 1.6. This magnetic field is much like that in the vicinity of a stationary bar magnet, although here **H** varies with time whereas that associated with a bar magnet is static. The time-varying magnetic field couples with a nearby metal test-piece and, in turn, induces electric current in the metal. This phenomenon of electromagnetic induction forms the foundation of eddy-current nondestructive evaluation. The eddy currents that flow in the metal are themselves time-varying and produce their own associated magnetic field, $\mathbf{H}_{ec}$. In an eddy current inspection, $\mathbf{H}_{ec}$ couples with a sensor—sometimes the induction coil itself—and the signal is interpreted to obtain physical information about the test-piece.

The fact that EC NDE works on the principle of electromagnetic induction means that it is inherently a noncontact inspection method. One advantage of this is that a test-piece may be inspected for damage even when covered by a protective layer of paint or some other type of cladding, for example.

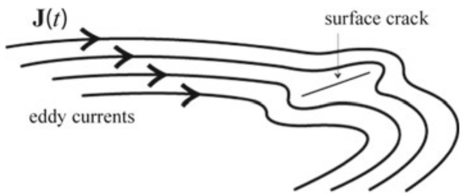

Fig. 1.7 Eddy currents disrupted by a surface defect. The eddy-current density $\mathbf{J}(t)$ is a vector field that is described in detail in Sect. 2.2

1.4 Eddy-Current Nondestructive Evaluation

Figure 1.5 shows eddy currents induced in an unflawed conductor. The existence of a defect such as a crack, some corrosion, a heat-affected zone or other inhomogeneity disrupts the flow of eddy currents, Fig. 1.7. In consequence, the magnetic field (Sect. 2.6) associated with the induced eddy currents, $\mathbf{H}_{\mathrm{ec}}$, is also disrupted. The total magnetic field can be written as the sum of that from the drive coil, $\mathbf{H}^0$, and that "scattered" by the defect, $\mathbf{H}^{\mathrm{s}}$:

$$\mathbf{H}_{\mathrm{ec}}(t) = \mathbf{H}^0(t) + \mathbf{H}^{\mathrm{s}}(t). \tag{1.1}$$

This disruption of the magnetic field may be detected by the inducing coil, or by another sensing or pick up coil specifically dedicated to measuring the flaw signal. A variety of defects can be detected in this way.

Note also that electromagnetic nondestructive evaluation methods can be used not only for flaw detection but also for the characterization of materials. With model-based or calibration methods it is possible to measure the electrical conductivity σ (or equivalently the resistivity $\rho = 1/\sigma$) of a metal, which is useful in identifying metal alloys. Thickness measurements can also be made under certain circumstances—useful when wall thinning due to corrosion is suspected. The distance between the coil and the metal part can be measured, which is useful for measuring the thickness of paint, for example.

1.5 Air-Cored Coil

The most basic eddy-current probe consists of a coil of wire wound on a nonconductive, nonmagnetic former, such as Delrin®. Such a coil is termed "air-cored" because the conductivity and permeability of the former are the same as those of air, to a close approximation. An image of such a coil, passing over a cracked test-piece, is shown in Fig. 1.8. Important parameters of the coil are its inner and outer radii, r_{i} and r_{o}, respectively, its length l, and number of turns (the number of loops of wire wound on the former) N. The minimum distance between the lower surface of the coil and the metal test-piece is determined by the thickness of the probe casing and is termed the probe "stand-off", s. A similar quantity is the coil "lift-off", h, usually

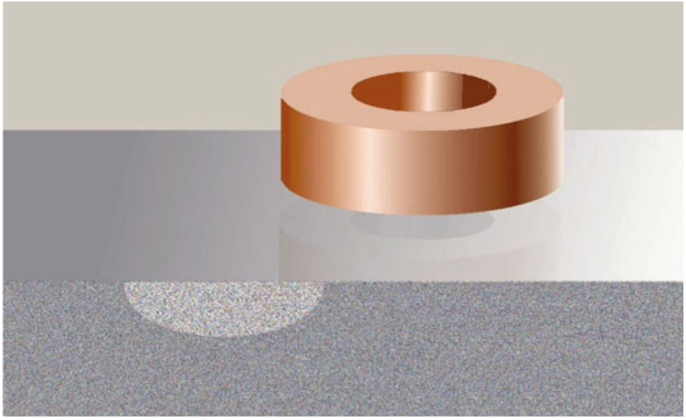

Fig. 1.8 Eddy-current coil passing over a test-piece with a surface crack

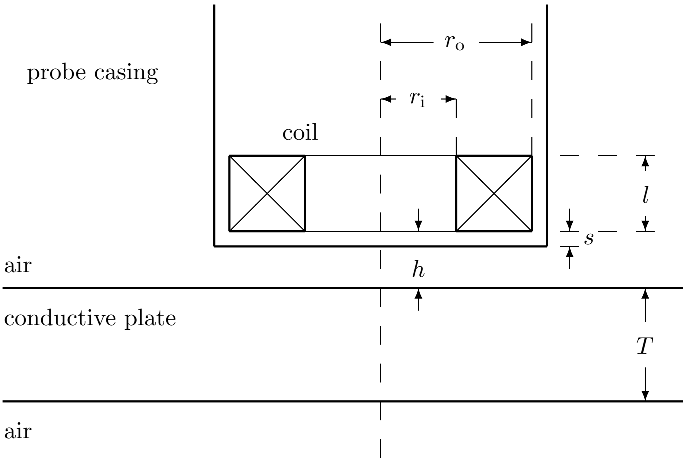

Fig. 1.9 Cross section through the axis of a circular, air-cored, eddy-current coil, positioned horizontally above a metal plate

defined to be the vertical distance between the lower surface of the coil windings and the metal test-piece. With this definition, $h \geq s$. A cross-sectional view of such a coil is shown schematically in Fig. 1.9. The coil parameters all affect the value of the coil impedance, Z, which is the quantity measured in a nondestructive eddy-current inspection and is generally a complex quantity. It is discussed in detail in Sect. 4.9. Z changes, for example, when a probe is placed on a metal sample from some distance away, and again when the probe moves near to a flaw in the metal. When the probe coil is sufficiently far from any metals that eddy currents are not induced by it, in practice, around 10 or 20 cm away depending on the coil, it is said to be *isolated* and its impedance has the symbol Z_0. For a sinusoidal (alternating current) excitation with angular frequency ω (Sect. 2.3), the component of Z_0 that is "in phase" with the variation of the exciting current is resistive, and the component that is "in quadrature" is inductive. This is represented in the following relationship:

$$Z_0 = R_0 + j\omega L_0 \tag{1.2}$$

where R_0 and L_0 are the d.c. resistance (Sect. 2.4) and inductance (Sect. 4.7) of the coil, respectively, and $j = \sqrt{-1}$. A theoretically "ideal" coil has $R_0 = 0$; it is a pure inductor:

$$Z_{\text{ideal}} = j\omega L_0. \tag{1.3}$$

In practice, the coil is usually made from a standard metal such as copper with finite resistance and, as the coil operating frequency increases, capacitance between the wires connecting the probe to any instrumentation, capacitance between the windings of the coil itself, and eddy currents in the wires themselves also exist. These effects, and a scheme by which corrections can be made for nonideal coil behavior, are discussed in detail in Chap. 8.

1.6 Summary

In this chapter, an introductory glance at the scope and history of EC NDE has been taken. In the next chapter, attention turns to visual representations and mathematical descriptions of the electromagnetic fields that Faraday conceptualized.

1.7 Exercises

1. On the same axes, sketch electric current (vertical) versus time (horizontal) for the currents flowing in circuits A and B of Faraday's transformer (Fig. 1.2) as the switch is first closed at time t_c and then opened at time t_o. Indicate the time points t_c and t_o on your plot. Remember that the current flowing in a circuit of this kind does not change instantaneously from "off" to "on" or vice versa, but has a finite transition time associated with its rise or fall.
2. Describe in your own words the phenomena observed, and the reasons for their occurrence, at each step of Faraday's experiment.

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