CH1. EDDY CURRENT INSPECTION METHODS
1. INTRODUCTION

The ability to quantitatively determine the location and shape of any flaw or internal structure within materials is important for both process control and in-service inspection of parts. Eddy currents and electromagnetic test techniques offer low-cost methods for inspection of metallic materials. In such industries as nuclear, aerospace and marine, eddy current techniques have been used to find defects in metals for a long time. In high pressure, high temperature and high speed engineering systems, the ability to avoid premature failures can mean enormous savings in both cost and human life.
1.1 Fundamental Eddy Current Concepts

The basic idea of eddy currents is to use a constant ac current source to excite a probe coil. The ac current in the coil produces an alternating magnetic field in accordance with the Maxwell-Ampere law. When the probe is placed in close proximity to metals, it induces within the test material a flow of electrical currents known as eddy currents \( (J = \sigma E) \) [Fig. 1.1]. These currents produce a magnetic field which in turn affects the original field. If the material is nonconducting and nonmagnetic \( (\sigma \approx 0, \mu_r \leq 1) \), no eddy currents are induced and eddy current NDE cannot be applied to such materials. If the material is conducting and nonmagnetic \( (\sigma > 0, \mu_r \leq 1) \) (e.g., copper, zinc, aluminum, titanium or stainless steel), the induced eddy currents provide a magnetic field which opposes a change in the net magnetic flux density.
Figure 1.1 Magnetic field coupling of eddy current probe coil and metals under test.
The coil impedance is the coil voltage divided by the constant drive current. Since the fields are affected by the presence of the work-piece, coil impedance is also affected. If the material is conducting and ferromagnetic \( (\sigma > 0, \mu_r > 1.001) \) (e.g., nickel, iron, cobalt, steel or ferrites), the exciting coil reactance changes in a different way than for nonmagnetic test materials. The flux lines within the magnetic material find portions of their path in such material with far less reluctance than air. This means that the path of flux lines are shortened, and then the magnetic flux density in the coil is increased. The coil inductance and inductive reactance increase dramatically when a highly permeable magnetic material is tested. However, if the frequency of ac current is high enough (up to one megahertz), the influence of eddy currents becomes predominant. The net effect is to decrease the inductance with increasing frequency [Fig. 1.2].
Figure 1.2  Impedance difference for a coil above metals and a coil in air. Eddy currents have a more complicated interaction with the ferromagnetic materials. The interaction depends on the frequency.
Eddy current NDE uses frequencies ranging from several hertz to megahertz \((10^1 – 10^7)\). In this low frequency range, the phenomena are governed by the *quasi-static* form of Maxwell's equations where the displacement current term \(\bar{D}'\) is assumed to be negligible. Consequently, the fields are governed by diffusion type equations rather than the wave equations of electromagnetic theory. In fact, an eddy current coil does not launch a wave. The fields decay exponentially inside metals. This decay is governed by a geometrical quantity called the *skin depth*, i.e.,

\[
\delta = \frac{1}{\sqrt{\pi j / \mu \sigma}}.
\]  

At one skin depth, the field intensity is \(1/e\) \((\sim 37\%)\) of its surface value. The skin effect phenomenon exists in all eddy current testing situations.
1.2 Eddy Current Inspection Techniques

Three advanced eddy current techniques have been under development in CNDE. They are **swept-frequency eddy current**, **pulsed eddy currents** and **photoinductive imaging** methods. Since the diffusion of eddy currents into metals is governed by the skin effect, the main idea of the swept-frequency eddy current (SFEC) method is to use a number of different frequencies to excite the coil. As shown in equation (1.1), the skin depth changes with frequency, conductivity and permeability of the materials under inspection. Hundreds of different frequencies in the eddy current frequency range are used to excite the coil. Lower frequencies have larger skin depth. They penetrate more deeply into the metals. Higher frequencies have smaller skin depth. They reflect the near surface situation. Consequently, swept-frequency eddy current technique can be used to determine depth information in metals.
Previous research showed that this technique can be successfully used to determine the thickness and conductivity of metallic coatings. As mentioned in the previous section, since eddy currents interact with ferromagnetic materials in a way that depends on the frequency, using this technique to characterize magnetic metals is a promising application. One example is using swept-frequency eddy currents (SFEC) to determine the initial permeability (metal permeability when the intensity of the applied field is weak) of ferromagnetic materials.
The pulsed eddy-current (PEC) technique is a time-domain method that gives similar information as the swept-frequency eddy current method. A step-function voltage is used to excite the coil. When transferred to the frequency domain, the step-function voltage covers a broad spectrum. It contains low frequencies as well as high frequencies [Fig. 1.3]. The main disadvantage of the swept-frequency eddy current method is the relatively long measurement time. The implementation of a frequency-domain eddy current method requires measurements of the absolute impedance of the coil using a computer-controlled HP 4194A impedance analyzer. Each measurement takes approximately 5–10 minutes. The same measurement by pulsed eddy current method can made much quicker. In principle, since we can finish one measurement by applying a step-function voltage (square wave with a 1 ms period), pulsed eddy current method can be thousands of times quicker than the swept-frequency eddy current method.
Figure 1.3 Step-function voltage and its frequency domain spectrum.