A Multi-Parameter Eddy Current Method for Monitoring Metal and Coating Degradation in Smart SHM Systems

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***Abstract*— In the context of smart cities, efficient structural health monitoring is crucial to ensure the safety and longevity of critical infrastructure. This work introduces an innovative Eddy Current Testing (ECT) method for real-time estimation of the electrical conductivity, thickness and lifting distance of metallic components. By applying Buckingham's π theorem, the approach enables accurate and low-cost monitoring, supporting predictive maintenance strategies essential for intelligent infrastructure management.**

Keywords—Eddy current, Non Destructive Testing, Structural Health Monitoring, Dimensional Analysis

I. Introduction

In the context of smart cities and the growing demand for intelligent infrastructure management, Structural Health Monitoring (SHM) is becoming a key milestone for ensuring the safety, durability and cost-effective maintenance of metal components of bridges, buildings, pipelines and transport systems [1]. Among the various degradation mechanisms affecting such structures, corrosion and the deterioration of protective coatings (such as paints or insulating layers) are particularly critical, often leading to compromised functionality and expensive repairs if not detected early [2].

This contribution presents a novel method for the simultaneous estimation of electrical conductivity, thickness of metallic samples, and the lift-off distance between the probe and the surface, using Eddy Current Testing (ECT). These parameters are essential indicators of both the material's condition and the integrity of surface treatments. Specifically, electrical conductivity and thickness are strongly affected by corrosion phenomena, which alter the material's microstructure and surface geometry, leading to measurable changes in its electromagnetic response [2]. Meanwhile, lift-off distance provides valuable insights into the presence, uniformity, or degradation of insulating coatings and painted layers [3], which are commonly employed to prevent corrosion or improve surface functionality.

The ability to measure these parameters in real time enables predictive maintenance strategies, reduces downtime, and enhances the operational efficiency of smart infrastructures. Despite the demand for such techniques, very few methods can simultaneously estimate different parameters in real-time. This is due to the complexity of handling ECT problems; indeed, (i) the relationship between the measured data and physical parameters is highly nonlinear, and (ii) the measurements are affected by many influencing variables.

In [4], dimensional analysis is introduced in the field of Non-Destructive Testing and Evaluation (NDT&E) for the first time. Specifically, Buckingham's π theorem [5] is shown to be the ideal tool to deal with this class of problems since it allows a systemic reduction of the number of variables needed to describe a physical problem.

This paper proposes a novel dimensionless multi-parameter ECT method that enables fast and accurate simultaneous estimation of electrical conductivity, thickness, and lift-off distance, providing a practical tool for real-time monitoring of metal and coating degradation in smart SHM systems.

II. Proposed Method and Experimental Results

In ECT, the measured quantity is represented by the variation in the mutual impedance ($\Delta\dot{Z}$) between the excitation and receiver coils, when placed in air and in the presence of a metallic plate. As already shown in [1], the measured impedance is related to several different quantities, i.e.

$$\Delta\dot{Z}/(N_1 N_2) = f(\omega, \sigma, \Delta h, \mu_0, D, l_o, \boldsymbol{t}) \quad (1)$$

where σ , Δh and μ_0 are the electrical conductivity, thickness and the magnetic permeability of the metallic plate, respectively; D, l_o and t are the typical linear dimension of the probes, the lift-off distance and the vector containing all the geometric parameters needed to describe the probes (thickness and height of the coils, internal radii), respectively, ω is the excitation frequency and N_1, N_2 are the number of turns of the two coils.

Throughout the application of the Buckingham's π theorem, relationship (1) can be recast as

$$\Delta \dot{Z}/N^2\omega\mu_0 D = F\left(D\sqrt{\omega\sigma\mu_0/2}, \Delta h/D, l_o/D, \boldsymbol{t}\right) \quad (2)$$

In other words, by recasting the problem in a dimensionless form (all the quantities in expression (2) are dimensionless), the number of dependent variables is decreased from seven in (1) to four in (2). Furthermore, by considering the geometrical parameters of the probe as known, the effect of the application of Buckingham's π theorem is even more evident, as the number of variables is decreased by 50% (six variables in the dimensional space, against three in the dimensionless space).

The proposed method has its roots in the simplification introduced by the above analysis. Indeed, in a three-dimensional space, an ad-hoc method can be introduced for the solution of the inverse problem. Specifically, the method heavily exploits the possibility of representing the relationship between the unknowns and the measured quantity in a dimensionless volume as level surfaces. The original problem is then recast in the intersection of level surfaces of proper real-valued functions of the dimensionless measured data, which can be computed with a negligible computational cost.

The proposed method has been validated through an extensive experimental campaign. Specifically, a GW-Instek 8000G impedance analyzer was employed, operating in slow acquisition mode and interfaced with a PC for automated data collection.

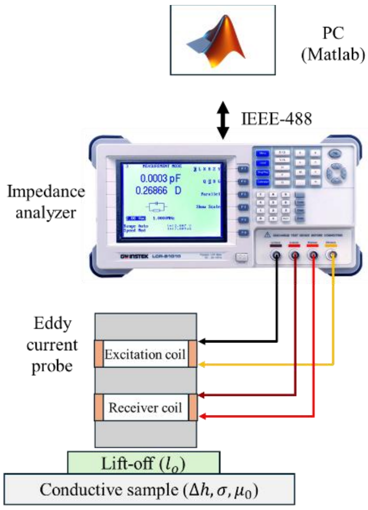

Fig. 1. Block diagram of the adopted experimental set-up.

The tests were performed on five conductive samples with electrical conductivities ranging from 17.45 MS/m to 58.05 MS/m, and at three different lift-off values between 0.59 mm and 1.58 mm. The adopted case studies are sample characterized by: (#a) σ = 17.45 MS/m , Δh = 2.025 mm, (#b) σ = 58.05 MS/m, Δh = 0.993 mm, (#c) σ = 28.01 MS/m, Δh = 1.979 mm, (#d) σ = 35.37 MS/m, Δh = 1.041 mm, (#e) σ = 35.09 MS/m, Δh = 1.971 mm.

Measurements were conducted over the frequency range of 400 Hz to 6 kHz, with frequency steps of 200 Hz. To ensure statistical robustness, each test was repeated five times. The results, averaged across repetitions and frequencies, demonstrate the accuracy and repeatability of the method (see Fig.2 (a)-(b)).

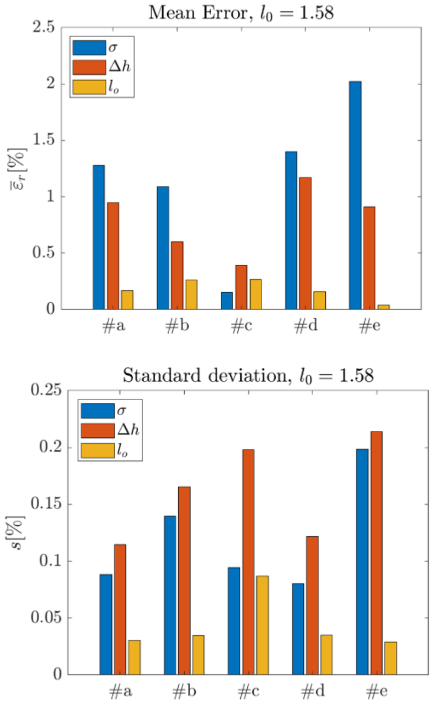

Fig. 2. Obtained experimental results considering the higher analyzed lift-off: (a) mean absolute relative error of the estimated quantities and (b) estimated relative standard deviations.

Experimental validation across various plates and lift-off distances demonstrates that the method combines rapid execution with high accuracy, fully aligned with the performance and reliability demands of smart city infrastructure.

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