Eddy current evaluation of metallic coating thicknesses over nonmagnetic metals

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Abstract. The use of titanium and nickel alloys in metal coating technologies have been gaining rapid popularity due to their high strength characteristics and excellent corrosion resistance behaviour operating at different temperature ranges. Phase-sensitive eddy current technique set by the International Organization for Standardization to assess metal coating thicknesses over nonmagnetic metals delivers \(\pm 30\%\) uncertainty in \(\pm 25.4 \, \mu\text{m}\) lift-off variation from that used over metal-coated calibration blocks. This study takes the first step towards adopting AECC spectroscopy as an alternative forward measurement technique, which offers a reduced sensitivity to lift-off and sample conductivity deviations from those used over the calibration blocks in a broad range of inspection frequencies. To map the depth-dependent conductivity profile from the frequency-dependent AECC measurement, a new AECC-based inversion algorithm is developed to estimate metallic coating thicknesses over nonmagnetic metals. This work is validated following the plane-wave approximation and COMSOL simulations over different coating thicknesses relevant to the industry. Results indicate that AECC spectroscopy can potentially deliver \(\pm 3\%\) uncertainty in metallic coating estimation in \(\pm 25.4 \, \mu\text{m}\) lift-off range. That is a significant improvement over existing eddy current measurement methods.

1. Introduction
Joining processes of dissimilar metals using metal spraying technologies \([1,2]\) and weld overlay \([3]\) are considered practical solutions in the design and manufacturing of critical components in Aviation and Oil and Gas industries. Their cost-effective solution to protect the functionality and life expectancy of their products make them even more attractive in the service sector of these industries. The growing demand for applying these technologies requires the use of a practical nondestructive evaluation approach to evaluate metallic coating thicknesses over nonmagnetic metals.

Phase-sensitive eddy current technology can be used to assess such nonmagnetic layered metal structures following ISO 21968 \([4]\). Impedance-based eddy current technology \([5]\) following Dodd and Deeds exact solution \([6,7]\) can also be used as alternative solution. The use of time-based pulsed eddy current technology has also demonstrated its potential capabilities to assess such structures \([8]\). Regardless of the eddy current technique used to assess these coating thicknesses, the calibration mandates building a coil-specific characteristic curve for a coating/substrate conductivity combination measured at a specific lift-off value, i.e., a known separation distance between the probe and the sample. Even with spring loading the probe against the sample to assure lift-off consistency between measurement and calibration, the measurement delivers an uncertainty in metal coating thickness.
estimation of approximately 13% [5,8].

Recent improvements in high-frequency eddy current conductivity spectroscopy delivers ± 0.1% uncertainty in apparent eddy current conductivity (AECC) up to 80-100 MHz in a ± 5% conductivity and ± 25 µm lift-off ranges [9-15]. Not only it allows the sample conductivity to deviate from those used over the calibration blocks, but it also allows enough lift-off variation consistent with the lift-off variations from spring loading the probe against the sample. The capabilities of AECC-based technology was initially built to assess 1-3% near-surface conductivity variations due to surface enhancement methodologies such as shot peening and low plasticity burnishing [16-18]. This study takes the first step towards building an AECC-based capability to assess metallic coating thicknesses over nonmagnetic metals.

2. AECC-based model
AECC over metallic-layered structure employs the analysis of an electromagnetic wave over depth-dependent inhomogeneous conductivity profiles. The previously mentioned AECC deals with the electric conductivity of a homogeneous medium that would produce the same complex coil impedance over an inhomogeneous medium at a given frequency [19]. The electromagnetic plane-wave approximation [20] has demonstrated its capabilities in capturing the AECC spectrum over small conductivity variations that are smooth and continuous (≤ 1% variation) as shown in figure 1. In other words, the plane-wave approximation assumes an infinitely large coil.

![Figure 1](image_url)

**Figure 1.** The use of the plane-wave approximation over (a) a continuous depth-dependent conductivity profile and (b) its corresponding AECC spectrum.

2.1. Forward model
The plane-wave approximation is considered as a direct approach to assess AECC spectrums. This study uses the same approach over step conductivity profiles, which represent conductivity profiles in coating/substrate metal structures. Figure 2 demonstrates the conductivity profile of a coating/substrate metal structure with relatively small conductivity variation. However, the challenge here is to validate the plane-wave approximation over relatively large conductivity variations.

For the case of titanium alloy over stainless steel, the coating will have a conductivity that is approximately 50% lower than the substrate. To validate the plane-wave approximation over this conductivity range with coating thicknesses (t) relevant to the industry, the indirect approach of AECC spectroscopy is followed. Linear system calibration is implemented using two calibration blocks to be measured with (l = 50.8 µm) and without (l = 0.0 µm) lift-off bracketing the coil impedance measured or simulated over the coated sample [15,20]. To cover the conductivity range of...
Figure 2. The use of the plane-wave approximation over (a) a step depth-dependent conductivity profile and (b) its corresponding AECC spectrum.

Figure 3. AECC spectrums using the plane-wave approximation (solid lines) and COMSOL simulations (open symbols) over different titanium coating thicknesses on stainless steel substrate.

interest with accuracy, 10 homogenous calibration blocks were simulated with and without lift-off. In this section, the coil impedance was simulated over the coated sample at 25.4 μm lift-off. A relatively large coil design was selected with 50-mm outer diameter to resemble the plane-wave approximation in an axisymmetric COMSOL model. The substrate was selected to be 10 times thicker than the eddy current standard penetration depth for the lowest frequency used in this study. This is considered to resemble the semi-infinite substrate used in the plane-wave approximation. A follow up study will address the challenges encountered upon reducing the coil outer diameter. System calibration and measurement simulations were implemented using the commercially available software COMSOL. Figure 3 shows the AECC change using the plane-wave approximation (solid lines) for different Ti-6Al-4V ($\sigma_c = 1.125\%$ IACS) coating thicknesses over semi-infinite SS304 ($\sigma_s = 2.250\%$ IACS).
substrate. Using the indirect approach of AECC assessment, COMSOL simulations (open symbols) show an excellent agreement with the plane-wave approximation. This indicates that AECC spectroscopy lends itself for coating thickness estimation over such metallic layered structures. In figure 3, the conductivity of SS304 substrate was used as a reference for AECC change simulations. The simulations at low frequencies will only see the conductivity of SS304. As the frequency increases, the effect of Ti-6Al-4V will reduce the AECC change. When the frequency is high enough, the AECC change will only see the conductivity of Ti-6Al-4V delivering -50% AECC change relative to the conductivity of the substrate.

2.2. Inverse model
Existing simple [20] and iterative [9] AECC-based inversion models only work for smooth and continuous depth-dependent conductivity profiles. In the case of step conductivity profiles, increasing the number of iterations increases the numerical instability after the 0th iteration, i.e., after applying the simplistic approach, as shown in figure 4. This indicates that existing inversion models are not suitable for step conductivity profiling applications. In the proposed model, it is assumed that the coating and substrate conductivities are known or measured separately. Accordingly, a best-fit analysis is implemented between a measured or COMSOL simulated AECC spectrum over an unknown coating thickness with the results of from the plane-wave approximation using the secant method. In this case, the whole AECC spectrum and two initial coating thickness points i.e., initial thickness guesses, bracketing the thickness of interest are needed to use the plane-wave approximation until its AECC spectrum converges to the measured or simulated AECC spectrum using the secant method.

Figure 4. A demonstration of existing AECC-based inversion models over (a) continuous and (b) step depth-dependent conductivity profiles.

3. Results and discussion
Figure 5 demonstrates the convergence of coating thickness estimation using the proposed AECC-based inversion model on a 0.2-mm titanium alloy coating thickness over a stainless steel substrate. It is worth mentioning here that it only takes few iterations to reach the accurate coating thickness. The estimated coating thickness was taken from a point measured or simulated at 25.4 µm lift-off, and delivered the accuracy shown in figure 5. To illustrate the robustness of the proposed method, figure 6 shows the average coating thickness estimates in a ±25.4 µm lift-off range. This is a significant improvement over other eddy current methods which only delivers a 13% uncertainty at fixed lift-off.
Figure 5. The convergence of coating thickness estimation using the secant method.

Figure 6. The lift-off effect on AECC-based estimates of coating thicknesses.

Table 1. Analysis of accuracy, precision and total uncertainty of the proposed method.

| Lift-off (l) [µm] | Analysis | \(t_{m}\) [mm] | \((t_{m})_{avg}\) [mm] | \(B_{x}\) [mm] | \(P_{x}\) [mm] | \(w_{x}\) [%] |
|------------------|----------|----------------|-----------------------|-------------|-------------|--------|
| 0.0              |          | 0.148 0.1460 0.1453 0.1486 0.1473 0.1467 0.1468 -0.0012 0.0036 2.56 |
| 12.7             |          | 0.222 0.2212 0.2202 0.2205 0.2216 0.2226 0.2212 -0.0008 0.0027 1.25 |
| 25.4             |          | 0.333 0.3330 0.3330 0.3328 0.3392 0.3328 0.3342 0.0012 0.0078 2.37 |
| 38.1             |          | 0.500 0.5054 0.5031 0.5031 0.5079 0.5124 0.5064 0.0064 0.0108 2.51 |
| 50.8             |          | 0.750 0.7674 0.7531 0.7672 0.7712 0.7682 0.7654 0.0154 0.0197 3.33 |

Table 1 illustrates a complete analysis of measured or estimated coating thicknesses \(t_{m}\) due to a ±25.4 µm lift-off range. Bias \(B_{x}\), precision \(P_{x}\) and total uncertainty \(w_{x}\) are included in this analysis. Since only 5 lift-off values are considered, Student’s \(t\) distribution at 95% confidence level is used in assessing the measurement precision. The average overall uncertainty equals to approximately 2.40% relative to the actual thickness \(t_{c}\).

4. Conclusions

AECC spectrums over conductive layered structures were simulated using two different approaches, namely the direct and indirect approaches. The simple direct approach uses the plane-wave approximation, which offers high accuracy in estimating AECC spectrums over coating/substrate metals. The indirect approach using COMSOL simulations with a relatively large coil design was used to validate the plane-wave approximation over 50% coating/substrate conductivity variations with coating thicknesses of interest to the industry. It was demonstrated that existing simplistic and iterative AECC-based inversion models only work for smooth and continuous conductivity profiles and are unfit to capture rectangular conductivity profiles in metallic coatings over nonmagnetic metals. The proposed AECC-based inversion model leverages the accuracy offered using the plane-wave approximation by applying best-fit analysis using the secant method to deliver the best agreement with the indirectly measured or simulated AECC spectrums. The proposed method delivers a ±3%
uncertainty in estimating metal coating thickness over nonmagnetic metals measured in a ±25.4 µm lift-off range. This is a one order of magnitude improvement over the applicable ISO standard for the same lift-off range.

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