Electromagnetic Model-Based Foreign Object Detection for Wireless Power Transfer

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Abstract—Foreign objects near wireless power transfer (WPT) systems are fire hazards that must be detected. In this article, a new accurate method is presented for foreign object detection based on an electromagnetic model for WPT. Foreign objects are detected by quantifying the deviation from a normal model. This deviation is caused by the foreign object’s additional electromagnetic coupling. Advantages of this new method include invariance to receiver coil misalignment, and power level, allowing low-power detection prior to startup. Electromagnetic model-based foreign object detection was demonstrated in hardware to detect a 2 cm diameter U.S. nickel coin, a small disposable lighter, and a saline proxy for a living animal in a kilowatt-level wireless power transfer system, using a prestartup power of only 7 W. Furthermore, foreign objects can be detected regardless of an Rx coil misalignment of up to 10 cm. This article is accompanied by an instructional video.

Index Terms—Charging, diagnostics, electric vehicles (EVs), electromagnetic modeling, faraday coil, foreign object detection, measurement, metal object detection, noncontact sensors, sense coil, wireless power transfer (WPT).

I. INTRODUCTION

SAFETY is vital in transportation. Wireless charging for electric vehicles has unique safety concerns in that a strong time-varying electromagnetic field for power transfer can threaten passenger safety. Foreign objects near magnetic wireless power transfer systems are one fire hazard because they can heat from eddy currents and cause a fire. This article presents an accurate and low-power low-risk foreign object detection for safe wireless power transfer.

Wireless power transfer (WPT) is predicted to emerge as the primary mode of electric vehicle (EV) charging [2]–[4] with safety as the main concern to adoption [5]. A foreign object near WPT should be detected for safety because it can cause a fire; an eddy current is induced by the time-varying electromagnetic field in the foreign object, where Joule heating from the eddy current can cause a fire in the foreign object itself [6] or near a flammable liquid. Regulatory standard SAE J2954 mandates foreign object detection (FOD) [7].

When foreign objects encroach (see Fig. 1), they perturb the electromagnetic field from that generated by the transmitter (Tx) and receiver (Rx) coil currents alone. This article uses this disturbance to derive a metric for FOD. An accurate electromagnetic model of magnetic WPT had been presented in [8] for transfer-power measurement (TPM), which consists of the Tx, Rx, and sense coils. A transformer model for the WPT coil voltages and currents is derived from the electromagnetic field, which can be reconstructed from a linear combination of sense coil voltages. We use this model as the normal model, which we extend to the adverse model by the inclusion of electromagnetic coupling from foreign objects. The deviation of the adverse model from the normal model, then indicates the measure of disturbance. This normal model is generally applicable to magnetic WPT [8], which has been shown to be invariant to power and Rx coil misalignment [9], thus making this electromagnetic model-based FOD (EM-FOD) appealing. Model-based fault detection, which is effective, reliable, and easily integrated with the existing systems, can be found in other applications such as switching power converters [10].

Several methods for FOD have been previously presented including using differences in the induced voltages of sets of sense coils [5], [6], [11]–[14], the impedance of the sensing patterns [15], the quality factor of the Rx coil [16], power or eddy current loss estimation [17]–[19], and variation in the Tx and Rx coil voltages and currents [20]–[22]. Lidar devices [23], radar sensors [24], thermal cameras [25], video sensors [26], cameras and image processing [27], and machine learning for reflection coefficient variation [28] are also used for FOD in WPT.

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There are challenges to these methods including the following:

1) risks in needing to resolve potentially small unsafe foreign objects by operating charging coils at high power for methods that directly use the voltage and current output of an electromagnetic sensor (e.g., sense coils);
2) large, expensive, or layered sensor arrays or grids to cover the area of interest if specific positions or coordinates are needed to identify the variations;
3) detection metrics that vary over Rx coil misalignment, which changes electromagnetic coupling hence affecting sensor impedance, mutual inductance, and power (or loss);
4) blind zones from sensor array symmetries such as with magnetically induced voltage differences between symmetric coil configurations;
5) expensive auxiliary systems with potential vulnerabilities to fouling, including cameras or image sensors to identify foreign objects through image detection.

EM-FOD employs two open-circuited single-turn sense coils to reconstruct the Tx coil current. For the reconstruction, sense coil voltages and geometric parameters, which encapsulate the electromagnetic couplings between the Tx, Rx, and sense coils, are required. When there is a foreign object, the Tx coil current reconstruction is no longer accurate because the geometric parameters do not represent the additional coupling from the eddy winding in the foreign object; this results in a \textit{sequent error}. The true Tx coil current is separately measured and compared to the reconstructed Tx coil current; the additional reconstruction error or \textit{sequent error} results from a foreign object because of additional electromagnetic coupling, hence becoming useful as the detection metric. Furthermore, by employing a few more sense coils (e.g., five sense coils), foreign objects can be detected accurately over Rx coil misalignment, where only sense coil voltages and Tx coil current are required to be measured.

EM-FOD has advantages which overcome the challenges of existing methods, including the following:

1) invariance to output loads, hence also power level, allowing low-power tests prior to startup;
2) invariance to coil misalignment;
3) wide dynamic range;
4) small number and small-sized sense coils whose electromagnetic contribution is negligible;
5) cost-effectiveness—using the same sense coils for metering (TPM);
6) no sensitivity dead-zones; all foreign objects within the electromagnetic space of WPT can be detected;
7) not needing Rx coil current and voltage information; only a service station’s Tx coil current is required, which is a measurement from something that does not move.

This article is organized as follows. Section II introduces the strategy of the electromagnetic FOD (EM-FOD). The Appendix A presents the theory of EM-FOD, specifically the theory of Tx coil current reconstruction and using the \textit{sequent error} as a detection metric for a foreign object are mathematically presented. Section III demonstrates EM-FOD using finite-element method (FEM) simulations by showing the \textit{sequent errors} in the Tx coil current reconstruction due to various foreign objects. Section IV presents the theory of accurate Tx coil current reconstruction over Rx coil misalignment when multiple sense coils are employed. Section V demonstrates an accurate EM-FOD at low operating power, which is low-risk. Section VI demonstrates EM-FOD in hardware over a standardized Rx coil misalignment\(^1\) of up to 10 cm. Finally, Section VII concludes the article.

\section{Foreign Object Detection Strategy}

Foreign objects can be detected by quantifying the deviation from the normal electromagnetic model for WPT. Fig. 2 shows the \textit{normal model} presented in [8] along with the extension to the \textit{adverse model} that includes the electromagnetic coupling of a foreign object.

The \textit{normal model} includes the Tx, Rx, and sense coils. The variables in the model are the Tx and Rx coil voltages and currents, which are derived from the electromagnetic field; a linear combination of sense coil voltages can reconstruct these voltages and currents [8].

The coupling between a foreign object and other coils can be analyzed by an eddy current winding model; the eddy current in the foreign object can be modeled as a transformer winding [29], [30], as shown in Fig. 2. The deviation of the \textit{adverse model} from the \textit{normal model} can then be quantified (discussed further in Appendix A). The geometric parameters are the coefficients used to reconstruct the Tx coil current from the linear combination of sense coil voltages, which contain a \textit{sequent error} in the \textit{adverse model}. The Tx coil current is chosen as the variable for comparison because of the following.

1) The Tx coil is stationary, inaccessible to users, and thus, secure.
2) The alternative of using the voltage measured at the electrical terminal of the coil results in an inaccurate reconstruction of the model because it contains not only the coil

\footnote{As specified in SAE J2954.}
voltage but also the voltage drops from winding and eddy losses [31], [32].

3) The Tx coil current can be reconstructed by nonvarying geometric parameters regardless of Rx coil misalignment. EM-FOD is practical for charging stations in that only sense coil voltages are required to be measured with a straightforward calibration of the geometric parameters in advance.

Calibration of the geometric parameters is initially performed in the normal model (no foreign objects); the parameters implicitly contain the magnetic and geometric information among the Tx, Rx, and sense coils. After calibration, EM-FOD uses measurements of the Tx coil current and sense coil voltages. Tx coil current is reconstructed from a linear combination of the sense coil voltages using the pre-calibrated (no foreign objects) geometric parameters. Foreign objects are detected from the sequent error between the measured and reconstructed Tx coil current; a foreign object in the electromagnetic space causes a sequent error from the additional coupling between the foreign object and other coils. Fig. 3 shows the EM-FOD strategy with the sequent error in the Tx coil current reconstruction as the detection metric.

The Appendix A elaborates on the mathematical derivations of the following: 1) the Tx coil current reconstruction using two sense coil voltages in the normal model; and 2) a sequent error in the adverse model.

An effective detection metric $\Gamma$ for EM-FOD can be chosen to be the sequent error in the Tx coil current reconstruction when normal geometric parameters $^2$ are used for the reconstruction. The detection metric $\Gamma$ is the absolute percentage sequent error $\epsilon_d$

$$\Gamma = \epsilon_d = \left| \frac{I_T - 1} {I_T} \right| \times 100 \text{ (%) } \quad (1)$$

where

$I_T$ : True Tx current measured by a current sensor;
$I_T$ : Reconstructed Tx current by sense coil voltages $V_1, V_2$

$\alpha_1 V_1 + \alpha_2 V_2$.

III. SIMULATION RESULTS

The EM-FOD was verified through FEM simulation in COM-SOL. Fig. 4 shows the configurations of the EM-FOD for the simulations. Two open-circuited sense coils (25 and 24 cm radii) were placed on the same flat plane, as shown in Fig. 5, which was 1 cm above the Tx coil. Four different foreign objects were placed on the ground, which was 5 cm above the Tx coil. Two-dimensional axisymmetric FEM simulations were performed, as shown in Fig. 6; sense coil voltages were obtained when the Tx and Rx coils were driven by current sources.

Following the EM-FOD strategy in Section II, the geometric parameters $(\alpha_1, \alpha_2)$ were calibrated initially in the normal model (no foreign objects). A sufficient number of data points were used to calibrate the geometric parameters accurately; in this simulation, the Rx coil currents were varied over $n$ data points, corresponding to different output load resistances in the Rx.

From the $n$ data points, the calibration data matrix of sense coil voltages $V$, the Tx coil current data vector $I_T$, and geometric parameters vector $\alpha$, can be constructed

$$V = \begin{bmatrix} V_1(z_1) & V_2(z_1) \\ V_1(z_2) & V_2(z_2) \\ \vdots & \vdots \\ V_1(z_n) & V_2(z_n) \end{bmatrix}$$

$$\alpha = [\alpha_1 \ \alpha_2]^T$$

$$I_T = \begin{bmatrix} I_T(z_1) \\ I_T(z_2) \\ \vdots \\ I_T(z_n) \end{bmatrix}^T. \quad (2)$$

From (26)

$$I_T = V \alpha. \quad (3)$$

The normal geometric parameters $(\alpha_1, \alpha_2)$ can then be calibrated using least-squares

$$\alpha = (V^T V)^{-1} V^T I_T. \quad (4)$$

To evaluate EM-FOD after calibration, the Tx coil currents were reconstructed with and without foreign objects using the normal geometric parameters. Note that in the EM-FOD detection metric $\Gamma$, defined in (40), $I_T'$ is the measured Tx coil current, which is the true value. In this simulation, the Rx coil currents were varied over 8 data points, which generated...
small Tx powers\(^3\) (2.1 to 3.54 W), as shown in Fig. 7(a); in the normal model (no foreign objects) (green-circles), the geometric parameters were calibrated, and then the Tx coil current was reconstructed; according to leave-one-out cross-validation (LOOCV) [33], this results in an accurate estimation.

\(^3\)The transmitter power is the real power, measured at the transmitter coil terminal.

Fig. 6. Two-dimensional axisymmetric FEM simulation of EM-FOD. The foreign object is electromagnetically coupled to the Tx, Rx, and sense coils. (In the colormap, the magnetic flux density norm was bounded for the better visualization.).

Fig. 7(a) shows that the EM-FOD detection metric $\Gamma$ increases significantly when a normal model has been calibrated and there are foreign objects. Note that the detection metric is plotted in logarithmic scale to highlight the wide dynamic range of the measurement.

Two additional data points, having higher Tx powers ($P_{Tx}$), were also tested to show the power-level invariance of EM-FOD; the Tx and Rx coil were driven by higher currents. The detection metric $\Gamma$ was calculated through (40), using the normal geometric parameters, calibrated at low power. Fig. 7(b) shows the detection metric did not change from that at low power;
a low-power test, which is safer and less hazardous can now be performed prior to startup. This is so because the sequent error from current reconstruction only depends on the additional electromagnetic coupling from the foreign objects, resulting in detection metric that is invariant to absolute power level.

IV. MISALIGNMENT INVARIANT EM-FOD

For a practical EM-FOD, adverse models need to be distinguished from what are considered ‘normal’ deviations from our original normal model. For example, Tx and Rx coil misalignment should be considered normal. In this section, we will show how a flat configuration of multiple sense coils on the same axis and plane can be used to eliminate a sequent error from misalignment. It is worth noting that in this method, explicit measurement of misalignment is not needed either for current reconstruction or calibration.

It is more practical to perform foreign object detection from a stationary system (i.e., energy service stations) rather than from an EV. EM-FOD is straightforward in that only sense coil voltages and Tx coil current measurements are needed for foreign object detection, requiring only an initial calibration.

Misalignment between the Tx and Rx coil can cause a sequent error in the Tx coil current reconstruction despite the absence of a foreign object when using only two sense coils. This is so because the geometric parameters, which are a function of the mutual inductances in (27) and (28), vary over misalignment. Fig. 8 shows the numerical results of the sequent error in the Tx coil current reconstruction over Rx coil misalignment when only two sense coils are used with the corresponding geometric parameters\(^ 4\) \(\alpha_1\) and \(\alpha_2\); the greater the misalignment, the larger the sequent error, despite there being no foreign object. The sequent error is no longer a good detection metric because of misalignment when only two sense coils are used.

By employing multiple sense coils, the Tx coil current can be reconstructed accurately with insignificant sequent error when the geometric parameters are nonvarying values over misalignment, resulting in a new normal model that considers the misalignment ‘normal.’ Foreign objects can then be detected regardless of misalignment.

A. Theory: Misalignment Invariant Detection Metric Using Sequent Error

Two sense coil voltages \(V_1, V_2\) can be mapped to the Tx coil current \(I_T\), where the linear mapping \(f\) is a function of a combination of the coils’ mutual inductances \(M\)

\[
\{V_1(x), V_2(x)\} \xrightarrow{f(M(x))} I_T(x).
\]  

In other words, \(I_T(x)\) is a linear combination of \(V_1\) and \(V_2\). The coefficients for this linear combination depend on the mutual inductances.

The mapping \(f\) for two sense coils changes with the Rx coil lateral misalignment \(x\) because the mutual inductances from the Rx coil to the Tx and sense coils vary over \(x\). If the individual mutual inductances vary over misalignment quadratically, then this mapping can be well-approximated by a quadratic function.

If we employ multiple \(N\) sense coils (e.g., \(N = 3\)), then the quadratic dependence of this mapping can be very nearly eliminated. In this circumstance, the linear mapping \(\lambda_i\) from the sense coil voltages becomes invariant to misalignment \(x\)

\[
\{V_i(x)\} \xrightarrow{\lambda_i} I_T(x).
\]  

Specifically, \(I_T(x)\) is a linear combination of sense coil voltages \(V_i(x)\), where \(\lambda_i\) are the coefficients that don’t vary with \(x\). Hence, the misalignment \(x\) is not explicitly needed to determine Tx current \(I_T\)

\[
I_T(x) = \sum_{i=1}^N \lambda_i V_i(x).
\]  

For EM-FOD, \(\lambda_i\) is determined from calibration. Calibration does not require explicit knowledge of the misalignment \(x\); only a sufficient number of calibration points that span the misalignment range are needed. Section IV-B details the calibration process.

The coils’ mutual inductance variations can be shown to be well-approximated by quadratic functions, as presented in [9] when multiple sense coils are coaxially placed relative to the Tx and Rx coils, as shown in Fig. 9. The mutual inductance between the Tx-to-Rx and Rx-to-sense coils are shown to be well-approximated by quadratic functions in Fig. 10. Note that the blue-dots, which are the mutual inductances directly calculated by the well-known numerical model for two circular filaments with lateral misalignment [34], are aligned with the red lines, the quadratic approximation obtained by the MATLAB Curve Fitting Toolbox (R2018b). Appendix B details the derivation steps of the Tx coil reconstruction using multiple sense coil voltages and constant coefficients over misalignment.

B. Numerical Model Verification

Numerical models,\(^ 5\) which were derived from a mutual inductance model [34], verify accurate Tx coil current reconstruction,

\(^4\)The geometric parameters are calibrated when the Tx and Rx coils are aligned, \(x = 0\). The sizes and positions of two sense coils are shown in Table I, where \(i = 1, 2\).

\(^5\)Assumptions in the numerical models are filament coils, fundamental only, and noiseless.
show that these additional sense coils eliminate the sequent error in lateral misalignments of up to 10 cm.

For the calibration of geometric parameters $\lambda_i$, numerical data were obtained over: (i) $n$ data points of the Rx coil current (corresponding to different load resistance); and (ii) $m$ data points of misalignment (not necessarily uniform). The calibration matrix and vector can then be constructed to solve the least-squares optimization in (56), when there are $N$ sense coils. The sense coil voltage measurements are combined in a data matrix

$$
V = \begin{bmatrix}
V_1(x_1, z_1) & V_2(x_1, z_1) & \ldots & V_N(x_1, z_1) \\
V_1(x_1, z_2) & V_2(x_1, z_2) & \ldots & V_N(x_1, z_2) \\
\vdots & \vdots & \ddots & \vdots \\
V_1(x_2, z_n) & V_2(x_2, z_n) & \ldots & V_N(x_2, z_n) \\
V_1(x_2, z_1) & V_2(x_2, z_1) & \ldots & V_N(x_2, z_1) \\
\vdots & \vdots & \ddots & \vdots \\
V_1(x_m, z_n) & V_2(x_m, z_n) & \ldots & V_N(x_m, z_n)
\end{bmatrix}
$$

(8)

The Tx coil current corresponding to each row of $V$ is contained in the elements of column vector $I_T$

$$
I_T = \begin{bmatrix}
I_T(x_1, z_1) \\
I_T(x_1, z_2) \\
\vdots \\
I_T(x_m, z_n)
\end{bmatrix}^T.
$$

(9)

Each row of $V$ corresponds to different measurement conditions such as misalignment and loads.

The vector of geometric parameters $\lambda_i$ for $N$ sense coils is

$$
\lambda = \begin{bmatrix}
\lambda_1 \\
\lambda_2 \\
\vdots \\
\lambda_N
\end{bmatrix}^T.
$$

(10)

From (55)

$$
I_T = V \lambda.
$$

(11)

The geometric parameters $(\lambda_i)$ can then be calibrated using the least-squares

$$
\lambda = (V^TV)^{-1}V^TI_T.
$$

(12)

The sequent error was determined for each data point using LOOCV$^6$ the absolute percentage sequent error of the Tx coil current reconstruction over Rx coil misalignment is

$$
\epsilon_d(x_m, z_n) = \left| \frac{I_T(x_m, z_n) - \hat{I}_T(x_m, z_n)}{I_T(x_m, z_n)} \right| \times 100 \, (\%) \tag{13}
$$

where

$$
\hat{I}_T(x_m, z_n) : \text{Reconstructed Tx coil current}
$$

$$
\hat{I}_T(x_m, z_n) = \sum_{i=1}^{N} \lambda_i V_i(x_m, z_n). \tag{14}
$$

$^6$If there are total $m \times n$ data points, then the calibration of the geometric parameters is performed with $m \times n - 1$ data points. The sequent error for Tx coil current reconstruction is evaluated with one data point which is not used for the calibration.
In this numerical model verification, \( n = 9 \) data points of the Rx coil current and \( m = 11 \) data points of misalignment (0 to 10 cm, 1 cm interval) were used to calibrate \( \lambda_i \).

The worst-case absolute sequent percentage error at each lateral misalignment \( x \) was calculated and plotted in Fig. 11, where

\[
|\epsilon_d(u)|_{\text{max}} \triangleq \max_k |\epsilon_d(u_k)|.
\] (15)

Note that \( u_k \) is the vector of variations over which the sequent error is calculated. In this plot, \( u_k = [x, z_k] \). With multiple sense coils and calibration over misalignment, the sequent error from misalignment decreased significantly. Moreover, as more sense coils were employed, the sequent error became negligible, i.e., \( 10^{-6}\% \) error, when five sense coils were used (green-upright triangles). This sequent error from misalignment represents the baseline for the foreign object detection metric \( \Gamma \).

V. HARDWARE RESULTS

EM-FOD was demonstrated in hardware. In this section, we demonstrate that foreign objects at three representative locations can be detected at a low pre-startup power level (7 W) by only two single-turn sense coils. The same foreign object detection is performed at a kW-level high power to show that the EM-FOD metric is power level invariant.

Sense coils consist of 42 AWG (0.06335 mm outer diameter) coaxial wires;\(^7\) they are single-turn, open-circuited, and placed on the same plane, which is 2.5 cm above the Tx coil, as shown in Figs. 12 and 13. Two sense coils (22.5 and 17.5 cm radii) were used to reconstruct the Tx coil current, where the radii of the Tx and Rx coils were 22.5 cm each.

The Tx and Rx coils were driven by identical current-mode class D (CMCD) converters \([36], [37]\), whose circuit diagram is shown in Fig. 14. The phase angle between two gate signals in one converter\(^8\) was maintained as 180° \([36]\). The phase angle of the gate signals between the Tx- and Rx-side CMCD converters \( S_1 \) and \( S_3 \) were adjusted to affect changes in the coil currents that correspond to different equivalent output load resistances to obtain the data for the calibration.

\(^7\)The braid of the coaxial cable, grounded on only one end, is used as an electrostatic shield from the high voltage Tx and Rx windings \([35]\).

\(^8\)The phase angles are: 1) between \( S_1 \) and \( S_2 \) pair in the Tx side CMCD converter; and 2) between \( S_3 \) and \( S_4 \) pair in the Rx side CMCD converter.
A single dc power supply held the shared voltage $V_{dc}$ for the dc input and output, where the dc output of the receiver CMCD converter was fed into the dc input of the transmitter. The power supply only supplied the power loss where the power contributing to the WPT circulated inside the loop. The entire EM-FOD testbed is shown in Fig. 15. The Tx coil current was measured by a current transformer (Pearson Model 110).

When the positions of the Tx and Rx coils were fixed, the geometric parameters $\alpha_1$ and $\alpha_2$ in the normal model in (27) and (28), i.e., with no foreign objects, were calibrated. After calibration, three different foreign objects: (i) 16 oz aluminum can; (ii) aluminum foil; and (iii) U.S. nickel coin, were placed in three different locations: (i) center; (ii) middle; and (iii) edge above the Tx coil, as shown in Figs. 16 and 17. The EM-FOD detection metric $\Gamma$, defined in (40), was calculated with and without foreign objects. The input dc power supply voltage ($V_{dc}$) was 25 V, and the operating frequency for WPT was 85 kHz, as specified in SAE J2954. The sense coil voltages and Tx coil current were recorded on an Elsys TraNET 204E, which provided 20 MHz sampling frequency with 16-bit resolution, as shown in Fig. 18.

Fig. 19 shows the experimental results. The Tx coil current reconstruction was accurate (0.007% for the worst-case experimental error, green-dashed line) when there was no foreign object. After the foreign objects were placed in the WPT system, the detection metric increased according to the volume and position of the foreign objects, which demonstrated that the metric indicates the quantity of electromagnetic coupling to the foreign objects. Note that the metric was plotted in logarithmic scale. When the 21 mm diameter U.S. nickel coin was placed on the center, the detection metric was at least 7 times higher than the metric without a foreign object. When the 16 oz aluminum can was located in the edge, the detection metric was more than
1000 times higher. It is worth noting that the pre-startup power level was low (7 W), meaning that a kW-level full-power test, which may be high-risk, is not necessarily needed. The power level was increased to a 1018 W to verify that EM-FOD is power level invariant. The input dc voltage was 302.5 V and the Tx coil current was 11.9 \( A_{\text{rms}} \), as shown in Fig. 20.

Fig. 20. Sense coil voltages and Tx coil current when the input Tx power was 1018 W. The Tx coil current was 11.9 \( A_{\text{rms}} \). The data were measured and recorded by a 20 Msample/s, 16-bit data acquisition system.

EM-FOD detection metric \( \Gamma \) at kW-level full-power was nearly invariant from the metric at the pre-startup power level of 7 W, to within experimental precision, as shown in Fig. 21, where the green-dashed lines are the reconstruction error from actual measurements without a foreign object.

EM-FOD can also detect a small piece of metal, ferrous objects, and a proxy for a living object. Using 7 W of input power, we tested the additional foreign objects shown in Fig. 22, including a small disposable lighter, steel pieces, and 0.9% saline water (500 mL) [38] in a 90 square inches resealable bag, which is a proxy for a small pet animal. The detection metrics for the various objects are presented in Table II. The small disposable lighter was also filled with no ignition occurring in any of the tests.

Fig. 21. Detection metric was invariant from low- to high-power levels. (a) Detection metric when 16 oz aluminum can and 9 square inches aluminum foil were examined. (b) Detection metric when 21 mm diameter U.S. nickel coin was examined.
power. This is results in a negligible temperature rise. If the entire input power of 7 W is dissipated in the saline water in the worst case, the energy dissipated is 6 J during the 0.839 s for the required detection in EM-FOD. This results in less than 0.003 °C temperature rise when the specific heat of 4.1 kJ/kg-K for 0.9% saline water [39] is used for the calculation.

VI. HARDWARE RESULTS: MISALIGNMENT INVARIENT EM-FOD

Misalignment invariant EM-FOD was also demonstrated in hardware using five-sense coils (radii of 22.5, 21.5, 20.5, 19.5, and 18.5 cm), which were placed on the same flat plane, as shown in Fig. 12. A 16 oz aluminum can, aluminum foil, and a U.S. nickel coin at the edge were tested with up to 10 cm lateral misalignment (based on SAE J2954) of the Rx coil, as shown in Fig. 23. Sense coil voltages and the Tx coil currents are shown in Fig. 24. When there was no foreign object, the geometric parameters, $\lambda_i$ were calibrated. After the calibration, the foreign objects were placed, and the Tx coil currents were reconstructed again at each misalignment.

Fig. 25 shows the hardware results. When there is no foreign object, the Tx coil currents are reconstructed accurately (0.06% worst-case error) over misalignment. As expected, the detection metric $\Gamma$ increases significantly when there is a foreign object. The metric is very nearly consistent over misalignment, which demonstrates misalignment invariant EM-FOD.

VII. CONCLUSION

An accurate and effective method for EM-FOD with wide dynamic range, which is invariant to power level and misalignment was presented in theory, simulation, and hardware. The detection metric that was presented for foreign object detection using the sequent error in the transmitter current reconstruction
is a result of the deviation to an adverse model from an easily calibrated, normal electromagnetic model.

**APPENDIX A**

**THEORY: DEVIATION FROM THE NORMAL ELECTROMAGNETIC MODEL**

A. Transmitter Current Reconstruction Using Sense Coil Voltages in the Normal Model

The Tx coil current $I_T$ can be reconstructed by two open-circuited sense coil voltages $V_1, V_2$. In the normal model, there are four windings which are electromagnetically coupled to the sense coils and hence induce the sense coil voltages: 1) the Tx coil; 2) the Rx coil; 3) the eddy current in the Tx coil, which is induced by the Rx coil current; and 4) the eddy current in the Rx coil, which is induced by the Tx coil current. It is worth noting that the time-varying Tx coil current forms the eddy current $I_t$ in the Rx coil as an external proximity effect. The Rx coil current also forms the eddy current $I_t$ in the Tx coil, as shown in Fig. 26. These eddy currents are also modeled as single windings [29], [30] which contribute to inducing the sense coil voltages.

The two sense coil voltages $^9 (V_1, V_2)$ in the normal model are superpositions of the induced voltages from the Tx, Rx, and eddy windings currents $(I_T, I_R, I_t, I_r)$

\[
V_1 = j\omega M_{T:1} I_T + j\omega M_{R:1} I_R + j\omega M_{t:1} I_t + j\omega M_{r:1} I_r
\]

\[
V_2 = j\omega M_{T:2} I_T + j\omega M_{R:2} I_R + j\omega M_{t:2} I_t + j\omega M_{r:2} I_r
\]

(16)

(17)

where each subscript $T$ and $R$ refer to the Tx and Rx coils, respectively; $t$ and $r$ refer to the eddy winding in the Tx and Rx coils, respectively; 1 and 2 refer to the sense coils; $M_{X:Y}$ is the mutual inductance between coils $X$ and $Y$. The eddy current $I_t$ and $I_r$ can be represented by the source coil current $I_R$ and $I_T$, respectively

\[
I_t = \frac{j\omega M_{R:t}}{-(Z_t + j\omega L_t)} I_R
\]

\[
I_r = \frac{j\omega M_{T:r}}{-(Z_r + j\omega L_r)} I_T
\]

(18)

(19)

where $M_{T:r}$ is the mutual inductance between the Tx coil and the eddy winding in the Rx coil; $M_{R:t}$ is the mutual inductance between the Rx coil and eddy winding in the Tx coil; $Z_t$ and $Z_r$ are the equivalent impedance in the Tx and Rx coil eddy winding. Using (18) and (19), the sense coil voltages in (16) and (17) can be represented by the Tx and Rx coil current

\[
V_1 = j\omega (M_{T:1} + m_{t:1}) I_T + j\omega (M_{R:1} + m_{r:1}) I_R
\]

\[
V_2 = j\omega (M_{T:2} + m_{t:2}) I_T + j\omega (M_{R:2} + m_{r:2}) I_R
\]

(20)

(21)

where

\[
m_{t:1} = \frac{j\omega M_{t:1} M_{R:t}}{-(R_t + j\omega L_t + j\omega X_t)}
\]

\[
m_{r:1} = \frac{j\omega M_{r:1} M_{T:r}}{-(R_r + j\omega L_r + j\omega X_r)}
\]

(22)

(23)

The Tx coil current can then be reconstructed as a linear combination of two sense coil voltages $V_1$ and $V_2$

\[
\begin{bmatrix} I_T \\ I_R \end{bmatrix} = \frac{1}{\mathcal{D}} \begin{bmatrix} M_{R:2} + m_{t:2} & -M_{R:1} - m_{t:1} \\ -M_{T:2} - m_{r:2} & M_{T:1} + m_{r:1} \end{bmatrix} \begin{bmatrix} V_1 \\ j\omega V_2 \end{bmatrix}
\]

(24)

where

\[
\mathcal{D} = (M_{T:1} + m_{r:1})(M_{R:2} + m_{t:2}) - (M_{R:1} + m_{t:1})(M_{T:2} + m_{r:2}).
\]

(25)

The Tx coil current $I_T$ can be rewritten using the normal geometric parameters $\alpha_i$

\[
I_T = \alpha_1 V_1 + \alpha_2 V_2
\]

(26)

where

\[
\alpha_1 = \frac{M_{R:2} + m_{t:2}}{j\omega \mathcal{D}}
\]

\[
\alpha_2 = -\frac{M_{R:1} + m_{t:1}}{j\omega \mathcal{D}}.
\]

(27)

(28)

It is worth noting that the eddy current $I_t$ in the Tx coil generated from the time-varying Rx coil current, and $I_r$ in the Rx coil generated from the time-varying Tx coil current can be significantly reduced if a litz wire with fine strands is used for the Tx and Rx windings. In this case, $m_{t:2}, m_{r:1}$ will be negligible.

B. Sequent Error in the Transmitter Current Reconstruction in the Adverse Model

The eddy winding of a foreign object (subscript: e) is included in the adverse model as shown in Fig. 2. The two sense coil...
voltages $V_1$ and $V_2$ then have the additional induced voltages (a) and (b) from the eddy winding current $I_e$

\[ V_1 = j\omega (M_{T,1} + m_{r,1}) I_T' + j\omega (M_{R,1} + m_{t,1}) I_R' + \frac{j\omega M_{e,1} I_e}{I_{e}} \]  
\[ V_2 = j\omega (M_{T,2} + m_{r,2}) I_T' + j\omega (M_{R,2} + m_{t,2}) I_R' + \frac{j\omega M_{e,2} I_e}{I_{e}} \]  

(29) (30)

where the Tx and Rx coil currents of the adverse model are $I_T'$ and $I_R'$, respectively. Then, (29) and (30) can be rewritten with respect to the deviation of the geometric parameter ($\Delta M_{X,i}$)

\[ V_1 = j\omega (M_{T,1} + m_{r,1} + \Delta M_{T,1}) I_T' + j\omega (M_{R,1} + m_{t,1} + \Delta M_{R,1}) I_R' \]  
\[ V_2 = j\omega (M_{T,2} + m_{r,2} + \Delta M_{T,2}) I_T' + j\omega (M_{R,2} + m_{t,2} + \Delta M_{R,2}) I_R' \]  

(31) (32)

where

\[ \Delta M_{X,i} = M_{X,e} M_{e,i} \frac{-j\omega Z_e - \omega^2 L_e}{Z_e^2 + \omega^2 L_e^2} \]  

(33)

Note that $I_e$ in (29) and (30) can be represented as the superposition of the Tx and Rx coil currents [30], which results in (33). The Tx coil current $I_T'$ of the adverse model is therefore

\[ I_T' = \alpha_1' V_1 + \alpha_2' V_2 \]  

(34)

where

\[ \alpha_1' = \frac{M_{R,2} + m_{t,2} + \Delta M_{R,2}}{j\omega D'} \]  
\[ \alpha_2' = \frac{-M_{R,1} - m_{t,1} - \Delta M_{R,1}}{j\omega D'} \]  
\[ D' = D + \Delta D \]  
\[ \Delta D = (M_{T,1} + m_{r,1}) \Delta M_{R,2} - (M_{R,1} + m_{t,1}) \Delta M_{T,2} + (M_{R,2} + m_{t,2}) \Delta M_{T,1} - (M_{T,2} + m_{r,2}) \Delta M_{R,1} + \Delta M_{T,1} \Delta M_{R,2} - \Delta M_{R,1} \Delta M_{T,2} \]  

(35) (36) (37) (38)

An effective detection metric $\Gamma$ for EM-FOD can be chosen to be the sequent error in Tx coil current reconstruction when normal geometric parameters $\alpha_1$ and $\alpha_2$ are used for the reconstruction. The reconstructed Tx coil current $I_T$ is

\[ \hat{I}_T = \alpha_1 V_1 + \alpha_2 V_2. \]  

(39)

The detection metric $\Gamma$ is the absolute percentage sequent error $\epsilon_d$

\[ \Gamma = \epsilon_d = \left| \frac{I_T' - \hat{I}_T}{I_T} \right| \times 100 \% \]  
\[ \Gamma = 1 - \left( \frac{D'}{D} - \zeta \right) \times 100 \% \]  

(40) (41)

where

\[ \zeta = \frac{\Delta M_{R,2}}{M_{R,2} + m_{t,2} + \Delta M_{R,2} - (M_{R,1} + m_{t,1}) \nu - \Delta M_{R,1} \nu} \]  
\[ \nu = \frac{M_{T,2} + m_{r,2} + \Delta M_{T,2} + (M_{R,2} + m_{t,2} + \Delta M_{R,2}) \gamma}{M_{T,1} + m_{r,1} + \Delta M_{T,1} + (M_{R,1} + m_{t,1} + \Delta M_{R,1}) \gamma} \]  
\[ \gamma = -\omega^2 M_{T,R} L_R - j\omega M_{T,R} Z_R \]  
\[ Z_R = \frac{Z_R^2}{Z_R^2 + \omega^2 L_R^2} \]  

(42) (43) (44)

$Z_R$ is the equivalent output impedance of the Rx coil. Note that if there is no foreign object, then $D' = D$, and $\zeta$ is zero, and therefore the relative sequent error goes to zero.

**APPENDIX B**

**THEORY: TX COIL CURRENT RECONSTRUCTION USING MULTIPLE SENSE COIL VOLTAGES AND CONSTANT COEFFICIENTS**

Sense coil voltages $V_i(x)$ at misalignment $x$, can be represented in terms of the Tx coil current $I_T$ and voltage $V_T$

\[ V_i(x) = j\omega M_{T,i} I_T(x) + j\omega M_{R,i} I_R(x) \]  
\[ = j\omega \left( M_{T,i} - \frac{M_{R,i}(x)}{M_{T,R}(x)} L_T \right) I_T(x) + \frac{M_{R,i}(x)}{M_{T,R}(x)} V_T(x) \]  

(45) (46)

where

\[ I_R(x) = \frac{V_T(x) - j\omega L_T I_T(x)}{j\omega M_{T,R}(x)}. \]  

(47)

Note that the mutual inductance between the Tx coil and sense coil, $M_{T,i}$ is constant over misalignment. The winding loss, which includes the ohmic loss and external proximity eddy current loss in the Tx and Rx coils are neglected\(^{10}\) to elucidate the principle of accurate Tx coil reconstruction over misalignment.

Equation (45) can be rewritten with the parameter $m_i(x)$

\[ V_i(x) = j\omega (M_{T,i} - m_i(x) L_T) I_T(x) + m_i(x) V_T(x) \]  

(48)

where

\[ m_i(x) = \frac{M_{R,i}(x)}{M_{T,R}(x)}. \]  

(49)

The parameter $m_i(x)$ can be well-approximated by a quadratic [9]

\[ m_i(x) \approx p_i + q_i x + r_i x^2 \]  

where $p, q, r \in \mathbb{R}$.\(^{10}\)

---

\(^{10}\)The eddy currents in the Tx and Rx coils are neglected; $I_t, I_r = 0$. 
$N$ sense coil voltages in (48) can be linearly combined by real coefficients $\beta_i$
\[
\sum_{i=1}^{N} \beta_i \frac{V_i(x)}{j\omega} = I_T(x) \sum_{i=1}^{N} (\beta_i M_{Ti} - \beta_i m_i(x) L_T) + V_T(x) \sum_{i=1}^{N} \beta_i m_i(x). \tag{51}
\]
$\beta_i$ for quadratically varying mutual inductance are found to be
\[
\sum_{i=1}^{N} \beta_i M_{Ti} \approx 1 \quad \sum_{i=1}^{N} \beta_i m_i(x) \approx 0 \tag{52}
\]
resulting in the reconstruction of the Tx coil current over misalignment $x$ by the sense coil voltages and the real coefficient $\beta_i$
\[
\sum_{i=1}^{N} \beta_i \frac{V_i(x)}{j\omega} \approx I_T(x). \tag{55}
\]
Note that new geometric parameters $\lambda_i = \beta_i/j\omega$ are constant and can be initially calibrated, meaning that the Tx coil current can be reconstructed at any misalignment $x$; only the geometric parameters and sense coil voltages are needed without explicit measurements of the misalignment.

A least-squares optimization is used to obtain $\lambda_i$
\[
\begin{align*}
\text{minimize} & \quad \left\| I_T(x) - \sum_{i=1}^{N} \lambda_i V_i(x) \right\|_2 \\
\text{subject to} & \quad \lambda_i \in \mathbb{C}. \end{align*} \tag{56}
\]

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