

UHF RFID Tag Antenna-Based Sensing for Corrosion Detection & Characterization Using Principal Component Analysis

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Abstract—Recently, structural health monitoring (SHM) using radio frequency identification (RFID) tag antenna-based sensing (TABS) has received increasing attention because of its wireless, passive, and low-cost characteristics. However, a great challenge in the SHM using RFID TABS is multiple influences in the measurement. This paper presents an ultrahigh frequency RFID sensor system for corrosion detection and characterization. In this paper, a 3-D antenna sensor is designed to work on the surface of a protective coated steel sample. Sweep-frequency measurements are applied for analog identifier with principal component analysis (PCA) to overcome the multiple influences from reader-tag orientation, distance, and environment. Feature extraction and selection through PCA can get robust and sensitive defect information by projecting the test data into an orthogonal feature space. The test results demonstrate that the proposed method can be applied to detect and characterize early-stage corrosion in metals.

Index Terms—Antenna sensor, corrosion detection, principal component analysis (PCA), radio frequency identification (RFID), structural health monitoring (SHM).

I. INTRODUCTION

STRUCTURAL health monitoring (SHM) and structural integrity evaluation (SIE) based on radio frequency identification (RFID) in the ultrahigh frequency (UHF) band are receiving more and more attention because of their wireless, passive, and low-cost characteristics. Integrating sensing ability in RFID tags renders the whole system capable of not only tracking, but also providing real-time cognition of aspects of object's status or environmental conditions [1], [2]. Recently, people's readiness to use RFID-based "smart skin" for *in situ* monitoring of the health state of large-scale infrastructure is increasing, thanks to the low cost and wide availability of RFID technology [3].

The last several decades have witnessed unprecedented prosperity in railway industry globally. Potential threats behind such a rapid expansion of railway network must be envisaged [4]. The surface of the rail web (cross section connecting the rail head with the foot) and foot (base support of the rail) can be wasted by corrosion, leading to fracture

and derailment [5], which will finally jeopardize the safety. Detection and characterization of corrosion is of paramount importance in railway track for safety and reliability of operation and maintenance. In contrast to conventional approaches of corrosion characterization considered as "metal loss," e.g., thickness changes [6], early-stage corrosion can be characterized by pitting corrosion [7], which leads to an increase in the surface roughness and reduction in the conductivity and permeability [8]. Electromagnetic (EM) nondestructive testing and evaluation (NDT&E) methods, such as pulsed eddy current [8], eddy current pulsed thermography (ECPT) [9], and microwave waveguide [10], can be used to detect and evaluate the corrosion. The experimental results have illustrated that these EM NDT&E methods are very effective to detect, evaluate, and predict the coated corrosion. However, it is difficult for these methods to permanently monitor corrosion due to the complex and bulky systems. Therefore, it is timely demanding to develop EM sensors that can be used to sense corrosion in order to undertake long-term/permanent-installed SHM and SIE. For railway monitoring, a large deployment of low-cost sensors is required owing to the large-scale structure. This makes passive RFID a good candidate among *in situ*, on-demand, and remote monitoring techniques [11].

Low frequency (LF) [12] and high frequency (HF) [13] RFID tag antenna-based sensing (TABS) were explored for detecting and characterizing corrosion under paint and insulation. Because of magnetic coupling (evanescent mode), the detection distance between LF/HF RFID tag and reader is quite short (in the range of several centimeters). UHF RFID TABS can be used to increase the monitoring distance resulting from EM coupling (radiation mode) [14]. The challenges of RFID sensor system for remotely monitoring the defects of metallic objects need to address the design and development of a metal-mountable antenna for both sensing and communication, to remote access for data collection (interrogation) with good signal-to-noise ratio subjected to environment interference, and to extract features for information required [15], [16]. Detailed challenges and progress of RFID antenna sensors and systems can be discussed below.

Contrary to the traditional metal-mountable antenna design, TABS takes advantage of the change underneath the tagged metallic objects [17]. The recent attempts to use UHF RFID tag antennas to monitor defects can be categorized into two main families: direct changes of antenna physical parameters and indirect changes of antenna property. For the former case, a flexible meander-line dipole was developed to monitor

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the strain with a submillimeter resolution [18]. The ink-jet printing [19] or embroidery technology [20] was applied to reduce the cost or improve the performance of strain sensors. However, the resolution and dynamic range of such a type of antennas may be influenced by each other. For the latter case, a microstrip antenna sensor was developed to monitor the growth of cracks with a sensitivity of 22 MHz/mm [21]. Moreover, a dual-resonant (TM01 and TM10 modes) microstrip antenna was proposed to detect the orientation of cracks and demonstrated that its sensitivity was related to the relative permittivity and geometrical length [22]. Further information about TABS can be found in [23].

The radio frequency (RF) signals carrying sensed information are backscattered into the wireless channel and RFID antenna sensors with the combination of sensing and communication in the system need addressing the RF channel to mitigate path loss and multipath effects [24]. In a multipath environment, backscatter RFID systems suffer from small-scale fading effects [25], which are more severe than in classical one-way systems. The backscattered signal is subject to environmental multipath en route reader that causes both frequency and time-selective effects [26]. As a result, multiantenna techniques in RFID-based systems have come into the focus of research to overcome this drawback [27]. This technology increases the design and manufacturing costs. Since backscattered power varies depending on the distance separation between the reader and the tag, a reference tag was used for differential measurement [28]. Without *a priori* information about the tag-reader mutual position, multiple measurements can be applied for separation and reduction of multiple influence. An analog identifier (AID) was invented for this purpose [29], which has been proved that AID is preferred among power metrics in terms of repeatability [30]. Benefited from a large variation of the tag chip impedance (nonlinearity), the influence from the environment may be mitigated by a double-power measurement technique [20].

The reader can continuously monitor the measurable parameters, e.g., forward power and backscatter power, and then features, such as resonant frequency shift (RFS), can be extracted and used to detect and characterize the defect. However, in the RFID sensor system, the contributions of the multiparameter from the defect mix with multiple influences from the environment. To this end, principal component analysis (PCA) and independent component analysis (ICA)-based pattern recognition algorithms can be used to extract the dominant variance and statistically separate the sensed signal from the interference, which have been applied in the field of NDT&E to analyze data from pulsed eddy current testing for detecting metal loss [31], cracks in multilayer structures [32], and corrosion [33]. More recently, PCA has been used to study the multiparameter effects of stress and defects in ECPT [34].

This paper is to address the challenges of detecting and characterizing corrosion in metals using RFID sensor system in terms of antenna design, system configuration, feature extraction, and corrosion characterization. A 3-D metal mountable tag antenna is proposed to optimize the tradeoff between sensing and communication. PCA is utilized to extract

the defect information from multiparameter signatures of corrosion in sweep-frequency measurements. The rest of this paper is organized as follows. At first, the sensing variable and PCA will be introduced in Section II. In Section III, antenna sensor design will be presented. After that, test setup will be illustrated and the test results using the proposed method will be discussed in Section IV. Finally, conclusions will be drawn and future work will be pointed out.

II. SENSING VARIABLE AND MULTIPARAMETER ANALYSIS

To develop RFID sensor system for corrosion detection and characterization, research work needs to cover tag antenna design for working on metallic surfaces with reasonable sensitivity and robust (signal) feature extraction for corrosion characterization independent of the interference. The former is left for discussion in the next section III, while the latter will be discussed in this section.

It is of paramount importance to mitigate multiple influences to get robust sensing information from the RFID sensor system. Several interferences, including sample surface geometry, multiple scattering due to nearby objects, and communication distance between the tag and the reader, are mixed, and thus, need to be separated.

The antenna sensor can sense the defect through the sensing variable, but the interferences change the impedance and radiation pattern of the antenna and, therefore, force the change in sensing variable as well. An analytical approach is applied to understand the measurable parameters and sensing variables. A robust sensing variable is selected.

At the same time, a mathematical processing that accounts for the effects of multiparameter signatures of corrosion is proposed. The PCA method with the help of sweep-frequency measurements is utilized to extract the dominant feature from the sensing variable. More details are explained in Sections II-A and II-B.

A. Sensing Variable

Under the hypothesis of line-of-sight propagation between the reader and tag antennas, the backscattered power in the free space by the Friis formula can be expressed as [35]

$$P_{R \leftarrow T}[\Psi(\theta, \phi)] = \frac{1}{4\pi} \left(\frac{\lambda_0}{4\pi d} \right)^2 \times P_{in} G_R^2(\theta, \phi) \eta_p^2 \text{RCS}[\Psi(\theta, \phi)] \quad (1)$$

where d is the reader-tag distance, λ_0 is the wavelength, P_{in} is the power transmitted by reader, $G_R(\theta, \phi)$ is the gain of the reader antenna, η_p is the polarization mismatch between the reader and tag antennas, and $\text{RCS}[\Psi(\theta, \phi)]$ is the radar cross section of the tag, which depends on [17]

$$\text{RCS}[\Psi(\theta, \phi)] = \frac{\lambda_0^2}{4\pi} G_T^2[\Psi(\theta, \phi)] \tau[\Psi] \frac{R_A[\Psi]}{R_L} \quad (2)$$

where Ψ represents the defect variable and $G_T[\Psi(\theta, \phi)]$ is the gain of the tag antenna. At the same time, the forward power to activate tag, i.e., P_{in}^{to} , can be written as

$$P_{in}^{to}[\Psi(\theta, \phi)] = \left(\frac{4\pi d}{\lambda_0} \right)^2 \times \frac{P_{th}}{G_R(\theta, \phi) G_T[\Psi(\theta, \phi)] \tau[\Psi] \eta_p} \quad (3)$$

where P_{th} is the minimum incident power needed to activate the tag chip (also called read sensitivity). The power transmission coefficient, which accounts for the impedance mismatching between the tag chip ($Z_L = R_L + jX_L$) and the tag antenna ($Z_A[\Psi] = R_A[\Psi] + jX_A[\Psi]$), is given by

$$\begin{aligned} \tau[\Psi] &= 1 - |S_{11}[\Psi]|^2 = 1 - \left| \frac{Z_L - Z_A^*[\Psi]}{Z_L + Z_A[\Psi]} \right|^2 \\ &= \frac{4R_L R_A[\Psi]}{|Z_L + Z_A[\Psi]|^2} \leq 1 \end{aligned} \quad (4)$$

where $Z_A^*[\Psi]$ is the conjugate value of the antenna impedance. The variation of the load impedance Z_L between the values Z_{L1} and Z_{L2} (load modulation) produces two different values of the power reflection coefficients ($\tau_1[\Psi]$ and $\tau_2[\Psi]$).

The differential radar cross section (ΔRCS) of an RFID tag is an important parameter, which determines the power of the modulated backscattered tag signal [36]. The ΔRCS can be expressed as [37]

$$\Delta\text{RCS}[\Psi(\theta, \phi)] = \frac{\lambda_0^2}{4\pi} G_T^2[\Psi(\theta, \phi)] |\tau_1[\Psi] - \tau_2[\Psi]|^2 \quad (5)$$

for both amplitude-shift-keying and phase shift-keying modulation. By means of *ad hoc* test-beds, it has been demonstrated that backscattered power exhibits a combined uncertainty ranging from 0.5 to 2 dB, with a deep dependence on the measurement instrumentation [30].

The measurement of ΔRCS suffers from the mutual distance and orientation between the reader and tag antennas. To address this issue, an indirect measurable parameter, independent of the reader-tag mutual position and orientation [35], can be obtained by combining the forward power (3) and the backscattered power (1)

$$\begin{aligned} \text{AID}[\Psi] &= \frac{P_{\text{th}}}{\sqrt{P_{\text{in}}^{\text{to}}[\Psi(\theta, \phi)] P_{R \leftarrow T}[\Psi(\theta, \phi)]}} \\ &= \frac{2R_L}{|Z_A[\Psi] + Z_L|}. \end{aligned} \quad (6)$$

In (6), $P_{R \leftarrow T}$ is the corresponding backscattered power in the tag's absorbing state, when $P_{\text{in}}^{\text{to}}$ is the turn ON power. $P_{R \leftarrow T}$ can be gathered, in principle, by the differential backscattered powers in the absorbing and reflecting states [17], or received signal strength indicator.

Comparing with $P_{R \leftarrow T}$, $P_{\text{in}}^{\text{to}}$, and ΔRCS , AID has a robust feature due to the ratio of power that is only related to impedance rather than antenna gain [15].

B. Multiparameter Analysis

The sensing mechanism of the UHF RFID TABS is similar to the pulsed eddy current technique [8], which uses alternating magnetic (evanescent) field to generate eddy current and then interacts with the sample. The surface roughness, thickness, conductivity, and permeability of steel and corroded area contribute to the variation of the tag antenna's impedance.

To simplify the analysis, the observation matrix is assumed to be a mixture of several sources, additive scatter, and noise

with mixing weight, m_i ($i = 1, 2, 3, 4$). The mathematical definition of the mixing model can be described as

$$Y = \sum_{i=1}^{N_S} m_i X_i + S + N \quad (7)$$

where $N_S = 4$ denotes the number of sources. $X_{1,2,3,4}(f)$ refers to the defect variable (Ψ), including thickness, surface roughness, conductivity, and permeability of corrosion layer and steel. $S(f)$ refers to the scatter caused by nearby objects and $N(f)$ represents noise, e.g., phase noise of the reader [38]. The first term of (7) is bearing the multiparameter defect information. The second term, nearby objects in the reader or tag, leads to an uncertainty in the measurement of forward and backscattered powers [39].

PCA is utilized to extract the dominant feature. The details of data processing method used in this paper are depicted in the following steps [40]:

- 1) Organize the data set as an $N \times M$ matrix, where N is the number of corrosion samples used and M is the number of the frequency points of the sweep-frequency measurement.
- 2) Normalize the data to have zero mean and unity variance.
- 3) Calculate the eigenvectors–eigenvalues of the covariance matrix by singular value decomposition.
- 4) Select the first and second eigenvectors corresponding to the first and second largest eigenvalues as the first principal component (PC1) and second principal component (PC2).
- 5) Transform the original data onto the selected PCs and obtain the corresponding projection coefficients (Ω_s).

Ω_1 and Ω_2 are selected as the new features, which represent the projections of AIDs onto the PC1 and PC2, respectively.

By projecting the measurement quantity into an orthogonal space spanned by the eigenvectors of the covariance matrix corresponding to the maximum variability within the data, PCA is used to extract the dominant variance from multiparameter signatures of the defect, to mitigate multiple effects from nearby objects, and to reduce the noise.

III. ANTENNA SENSOR DESIGN

In Section II, we analyzed a robust sensing variable and feature extraction method. To design a specific antenna with a reasonable sensitivity and communication distance, the physical, chemical, and electrical properties of the corrosion sample need to be taken into consideration. With the help of simulation, this section presents the EM modeling of corrosion stages, the design rule of a prototype antenna sensor, and the optimization procedure to balance the tradeoff between sensing and communication.

A. Sample Preparation

Corrosion in steel is a general term for a series of iron oxides (hematite $\alpha\text{-Fe}_2\text{O}_3$, magnetite Fe_3O_4 , and maghemite $\gamma\text{-Fe}_2\text{O}_3$) and hydroxides [ferrous hydroxide $\text{Fe}(\text{OH})$,

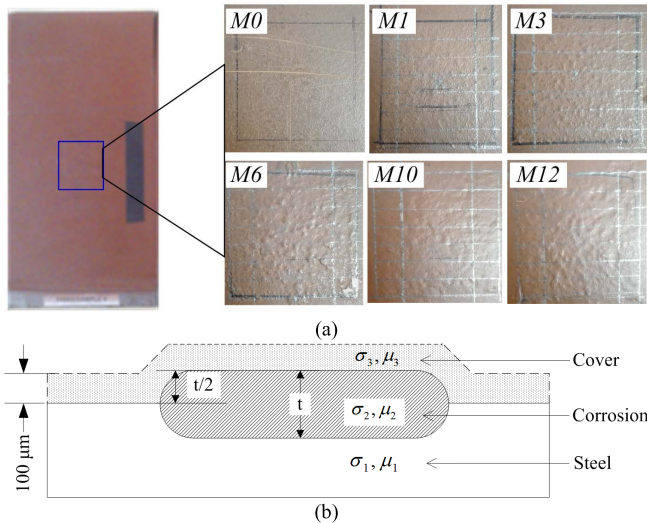


Fig. 1. (a) Corrosion samples in six different stages and (b) simplified model.

ferric hydroxide $\text{Fe}(\text{OH})_3$, and goethite $\alpha\text{-FeOOH}$], and over time only the proportions of the corrosion constituents change, there is little effect on the composition [8].

According to [41], the electrical conductivity and relative permeability of steel are 4.68×10^6 S/m and 60, while the electrical conductivity and relative permeability of corrosion are about 0.75×10^6 S/m and 4, respectively. Therefore, the skin depth is about $0.9 \mu\text{m}$ in steel and approximately $9.2 \mu\text{m}$ in corroded area at 1 GHz. The effect of the loss from eddy current induced by surface roughness can be neglected, if their dimensions are not comparable, on the average, to the skin depth [42]. Because of the increase in the surface roughness, the conductivity of the corroded area will decrease with the corrosion progression.

The samples (mild steel S275) used in this paper, with length \times width \times height of $300 \text{ mm} \times 150 \text{ mm} \times 3 \text{ mm}$, are provided by International Paint [Fig. 1(a)], the center part (corroded area with a size of $30 \text{ mm} \times 30 \text{ mm}$) of which was exposed to a marine atmosphere for a certain time (0, 1, 3, 6, 10, and 12 months), and then, covered using a nonconductive paint in a thickness of $\sim 100 \mu\text{m}$. For reference convenience, these six-stage samples are, respectively, represented as *M0*, *M1*, *M3*, *M6*, *M10*, and *M12*. The corrosion samples can be divided into two categories [43]: early stage (*M0*, *M1*, *M3*, and *M6*) and later stage (*M10* and *M12*).

To facilitate early detection and characterization of corrosion, this paper focuses on the early-stage ones, where pitting corrosion is dominant. At this stage, the corrosion layer thickness (t) increases as corrosion progresses [8]. This parameter becomes an interesting signature to be measured. For simplicity, the covering layer can be treated as a dry-air film and the corrosion sample is, therefore, modeled as a multilayered structure, which is depicted in Fig. 1(b).

B. Antenna Design for Sensing and Communication

To achieve an optimal tradeoff between sensing and communication is a major consideration in the design of an antenna sensor. The proximity coupling between the antenna and the tagged object can be utilized for sensing purpose when

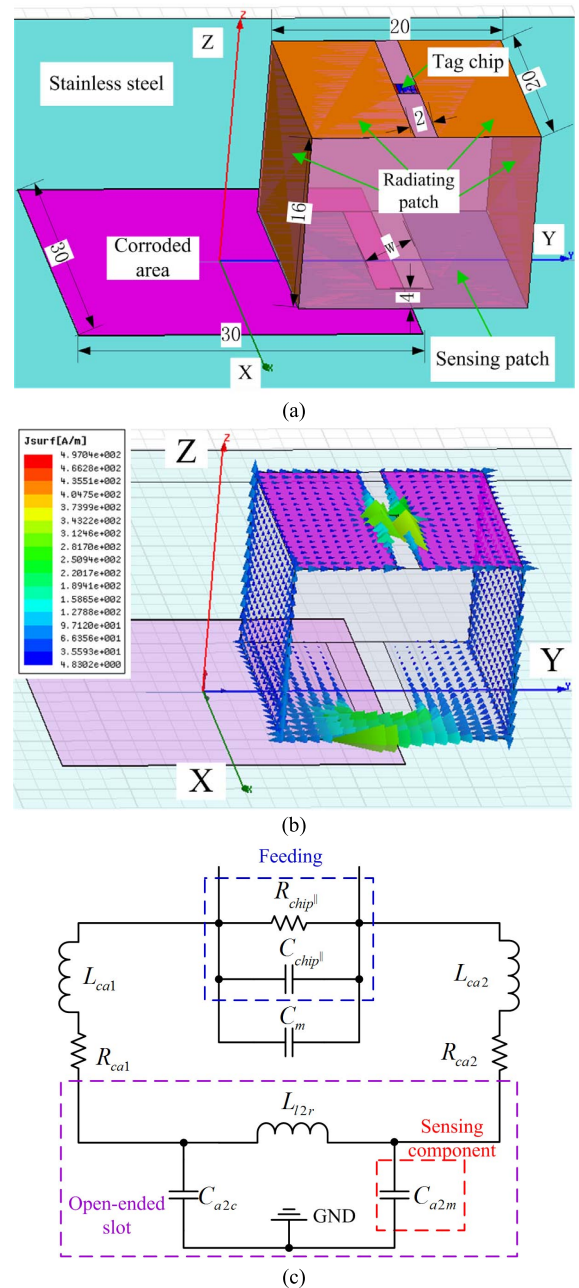


Fig. 2. (a) Proposed 3-D metal mountable UHF RFID tag antenna. (b) Simulated current distribution. (c) Equivalent circuit, where $C_m = 0.57 \text{ pF}$, $L_{ca1} = 6.81 \text{ nH}$, $R_{ca1} = 1.08 \Omega$, $L_{ca2} = 6.81 \text{ nH}$, $R_{ca2} = 1.08 \Omega$, $C_{a2c} = 14.45 \text{ pF}$, $L_{12r} = 1.67 \text{ nH}$, and $C_{a2m} = 15.70 \text{ pF}$ at $w = 5 \text{ mm}$ and $t = 40 \mu\text{m}$.

disturbance underneath the antenna sensor occurs at a presence of corrosion. The high-quality-factor antenna offers a better sensitivity for sensing, but can be costly to implement and difficult to attach to the surface of a flat metallic structure [44]. Owing to the edge effect [45], the antenna size needs to be reduced down to corrosion patch to maximize the sensitivity. For these reasons, the antenna should be electrically small in order to be more sensitive. In addition, the cost consideration in manufacturing requires a simple antenna structure as well as use of lossy substrate materials. This will substantially reduce

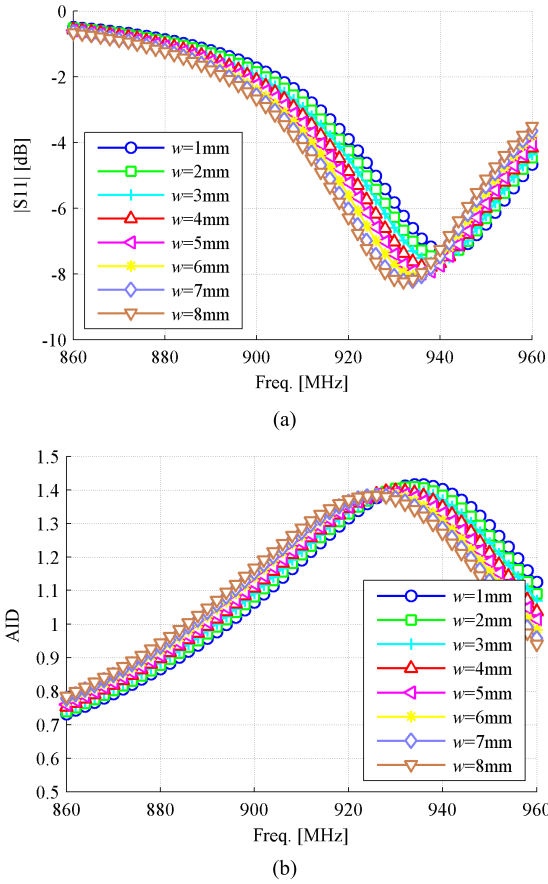


Fig. 3. Simulated (a) reflection coefficients (S11) and (b) AIDs in the variation of w when $t = 40 \mu\text{m}$.

the communication distance. In complementary, a larger height profile (aspect ratio) is required to enhance the reading performance [46]. This may also lead to a quasi-omnidirectional radiation pattern above tagged object, allowing tag to be easily identified.

A 3-D cage antenna is proposed to facilitate the size reduction and to be conjugately matched with a capacitive load, i.e., tag chip. The antenna is prototyped for conjugate impedance matching to the passive tag chip of IMPINJ MONZA 4QT in the single-port connection, the input impedance (Z_L) and nominal read sensitivity (P_{th}) of which are $11 - j143 \Omega$ and -17.4 dBm at 915 MHz, respectively. The equivalent input impedance of this chip can be treated as a $1.65\text{-k}\Omega$ resistor connected in parallel with a 1.21-pF capacitor [47]. An FR4 material, with a loss tangent of 0.02 and a relative permittivity of 4.4, is used in this design. The proposed antenna is shown in Fig. 2(a), the substrate of which consists of ten layers of FR4 lamination, with a standard thickness of 1.6 mm for each layer. The total size of the antenna is $20 \text{ mm} \times 20 \text{ mm} \times 16 \text{ mm}$. The reason for the selection of the height profile (h) will be further discussed from sensing point of view in the next part.

To enable the sensing ability for such a tag antenna, an open-ended slot is first etched on the sensing patch, as shown in Fig. 2(a). Consequently, an enhancement in the current distribution can be formed near the slot [see Fig. 2(b)]. Second, we deploy the antenna in the edge of corroded area; hence,

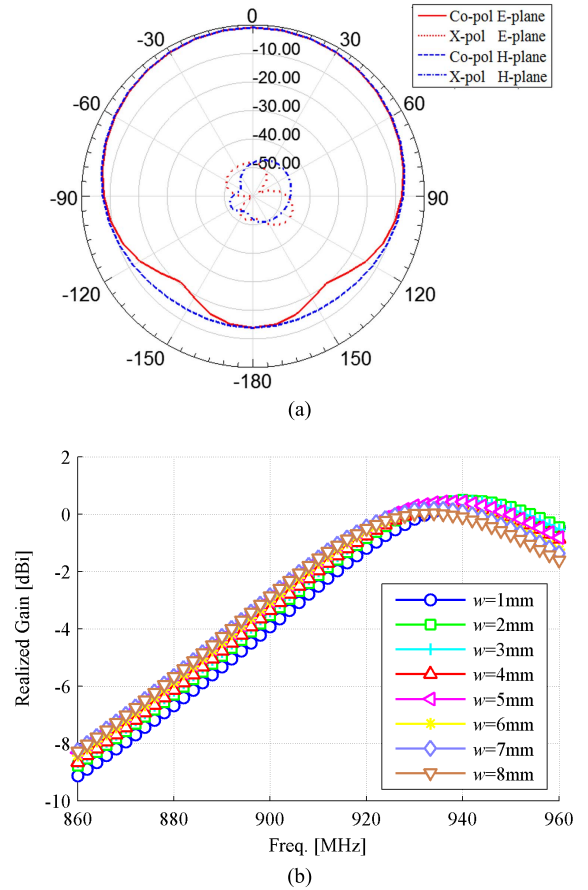


Fig. 4. (a) Simulated radiation pattern at 915 MHz when $w = 5 \text{ mm}$ and $t = 40 \mu\text{m}$. (b) Simulated realized gain versus frequency in the variation of w when $t = 40 \mu\text{m}$.

the corrosion and steel will, respectively, affect the left and right parts of the sensing patch, and thus, generates an uneven current distribution in this patch. Since the antenna is directly mounted on the corrosion sample, the distance of the antenna to the corroded area is fixed. Using such a configuration, we can measure the thickness difference between the corrosion layer and the base material (steel).

The lumped circuit analogy is given out in Fig. 2(c) to gain a physical insight into the operation of the proposed antenna sensor and find the variation of the sensing variable as corrosion progresses. We can generate an equivalent circuit model for the proposed antenna sensor by starting from the cage structure, where C_m represents the feeding gap, L_{cax} and R_{cax} ($x = 1, 2$) represent the inductance and resistance (including loss) of the cage structure. The displacement and longitudinal current in the open-ended slot can be, respectively, modeled by two parallel capacitors and one inductor in series connected in between. C_{a2c} is to account for the capacitive coupling of the antenna to the corroded area, C_{a2m} is to account for the capacitive coupling between the antenna and the base material (steel), and L_{l2r} is to account for the strip connected the left and right parts of the sensing patch, which is influenced by the slot with (w). The parameter of interest, i.e., t , can be quantified by the sensing component of C_{a2m} . Consequently,

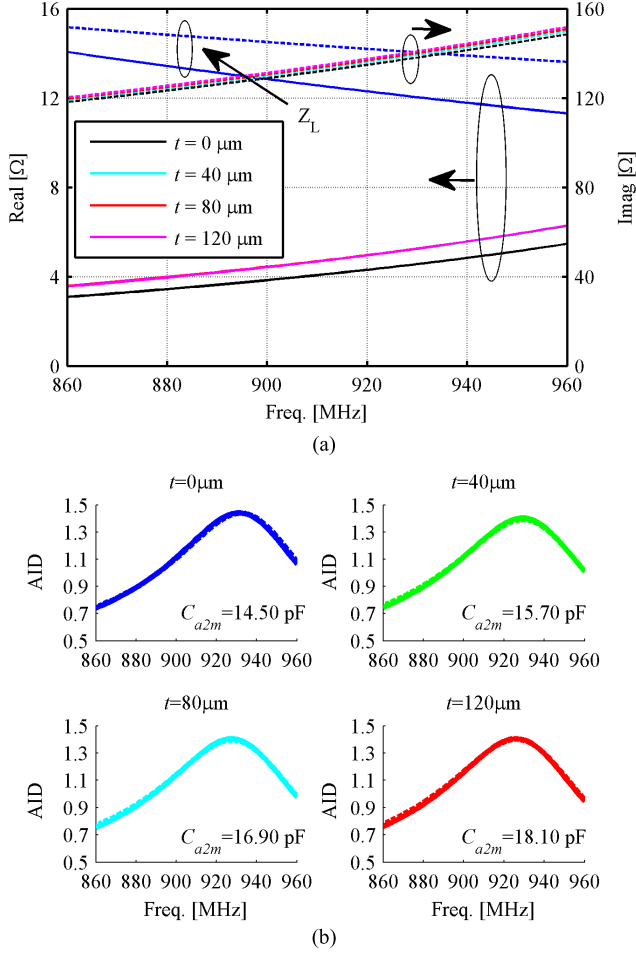


Fig. 5. (a) Simulated input impedances of the proposed antenna sensor versus frequency in the variation of t when $w = 5$ mm. (b) Simulated and modeled AIDs versus frequency in the variation of t when $w = 5$ mm. Solid line: simulated results. Dashed line: modeled ones.

it varies along with corrosion progression, which will influence the impedance matching of the antenna, and thus, can be indirectly measured via the sensing variable, i.e., AID.

C. Forward Problem Analysis for Optimization

Fig. 3 shows the simulated reflection coefficients (S11) and AIDs of the proposed antenna. The simulated 3-dB impedance bandwidth of the proposed antenna is larger than 50 MHz. It is straightforward that the resonant frequency of the proposed antenna drops as an increase of h owing to the increase of the inductance [L_{cax} in Fig. 2(c)]. Besides, because of an increase in L_{l2r} , the resonant frequency of the antenna will slightly decrease as w increases.

The simulated radiation pattern and realized gain, which have taken into consideration the impedance mismatch loss between the antenna and the tag chip [48], are depicted in Fig. 4(a) and (b), respectively. The nondirectional radiation pattern, resulting from the radiation in both horizontal and vertical radiating patches, makes the tag be easily identified in a wide range of spatial angles in both E (yz) and H (xz) planes [see Fig. 4(a)]. From Fig. 4(b), we see that the proposed

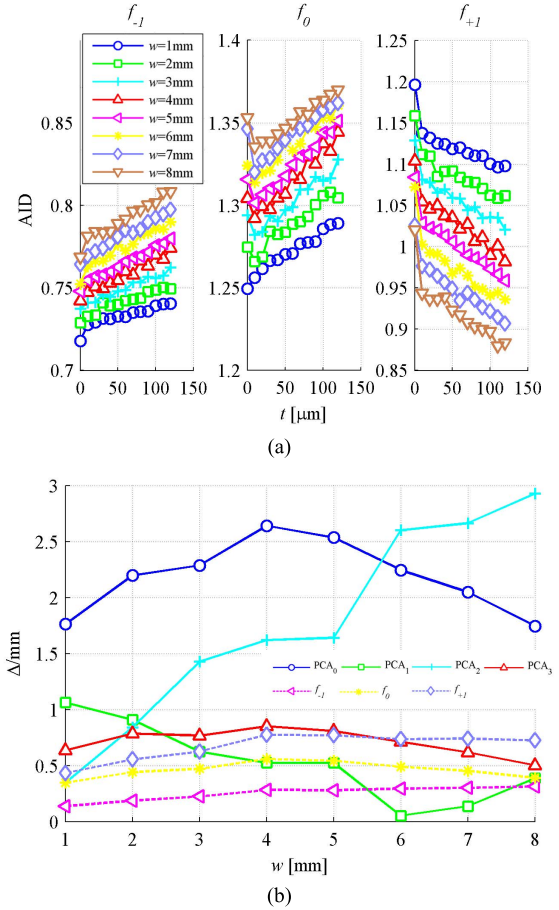


Fig. 6. (a) Simulated AIDs versus t in the variation of w , where $f_{-1} = 860$ MHz, $f_0 = 915$ MHz, and $f_{+1} = 960$ MHz. (b) Sensitivities of different features, where PCA_0 and PCA_3 represent the feature of Ω_1 , respectively, extracted from the frequency band of 902–928 and 860–960 MHz when $h = 16.0$ mm, while PCA_1 and PCA_2 represent the feature of Ω_1 extracted from the frequency band of 902–928 MHz when h is 16.5 and 17 mm, respectively.

antenna can reach its peak realized gain of 0.6 dBi at 934 MHz. The reason for the selection of w will be discussed later in this section. Nevertheless, we can find that the peak realized gain slightly decreases with the increase of w .

Fig. 5(a) shows the simulated input impedances of the proposed antenna sensor in the variation of t . It can be observed that a substantial change in the resistance occurs when corrosion happens. This is directly caused by a significant reduction in the resistance of R_{ca1} from 1.30 Ω at the healthy state and to 1.08 Ω at the corrosion states (and maintained almost at different corrosion stages), which can be attributed to a reduction of eddy current loss at a presence of corrosion.

Fig. 5(b) shows a comparison of the simulated results of AIDs using full wave simulation with the results using an equivalent circuit model. Good agreement can be found, which demonstrates that the sensing principle can be reasonably reconstructed in terms of a capacitive sensing component. The increase in t leads to an increase in the displacement current (due to the cavity theory), thus rendering an increase in C_{a2m} . This drops the resonant frequency as corrosion progresses.

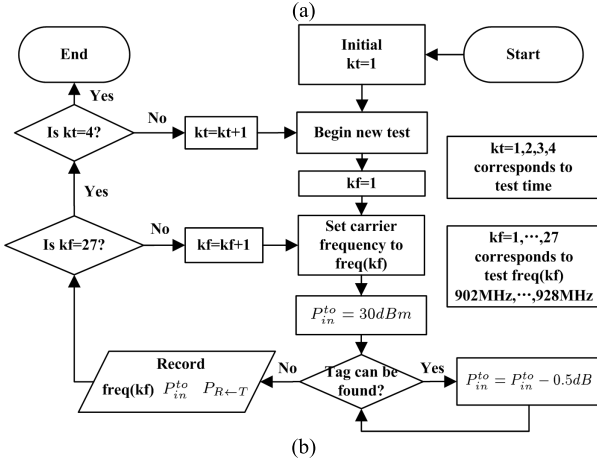
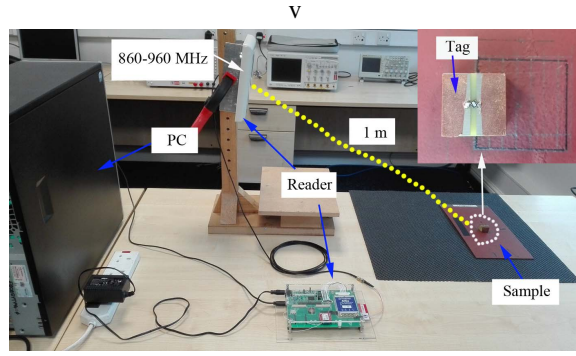


Fig. 7. (a) Hardware measurement setup. (b) Software flowchart of the RFID sensor system.

Fig. 6(a) shows a feature of single frequency (SF) directly extracted from AID. It can be found that the corrosion layer thickness produces a monotonic shift in AID in the frequency away from resonance. Therefore, SF (or RFS) can be used to act as a feature to *detect* and *characterize* the corrosion in metals. To compare the sensitivity of Ω_1 and SF, a min-max normalization method is used in its feasible region to conduct a dimensionless analysis, and the results are shown in Fig. 6(b). We see that the sensitivity of SF increases with the increase of w and reaches the peak value when $w = 4$ mm. However, it is not maximized near the resonant frequency (e.g., f_0), which complicates the selection of frequency points, particularly in autonomous scenarios, and also leads to a tradeoff between sensing (sensitivity) and communication (distance).

Similarly, by comparing PCA_0 , PCA_1 , and PCA_2 , we can find that the sensitivity of the PCA method is related to the resonant frequency (or h). In contrary to the feature of SF, the PCA method uses the shape information; hence its sensitivity can be maximized even a small bandwidth is available, e.g., 902–928 MHz in this paper. Therefore, to achieve an optimal tradeoff between sensing and communication, the proposed antenna is tuned to resonate at 934 MHz at the healthy state, a little higher than the upper bound of the measurable frequency region. Meanwhile, a slot width of 5 mm is selected for the experimental study to ease the deployment of the tag. This is also attributed to the reason where the corrosion that happens is unknown in *a priori* for practical applications.

By properly choosing the antenna size and topology (radiation mode), designing the matching performance,

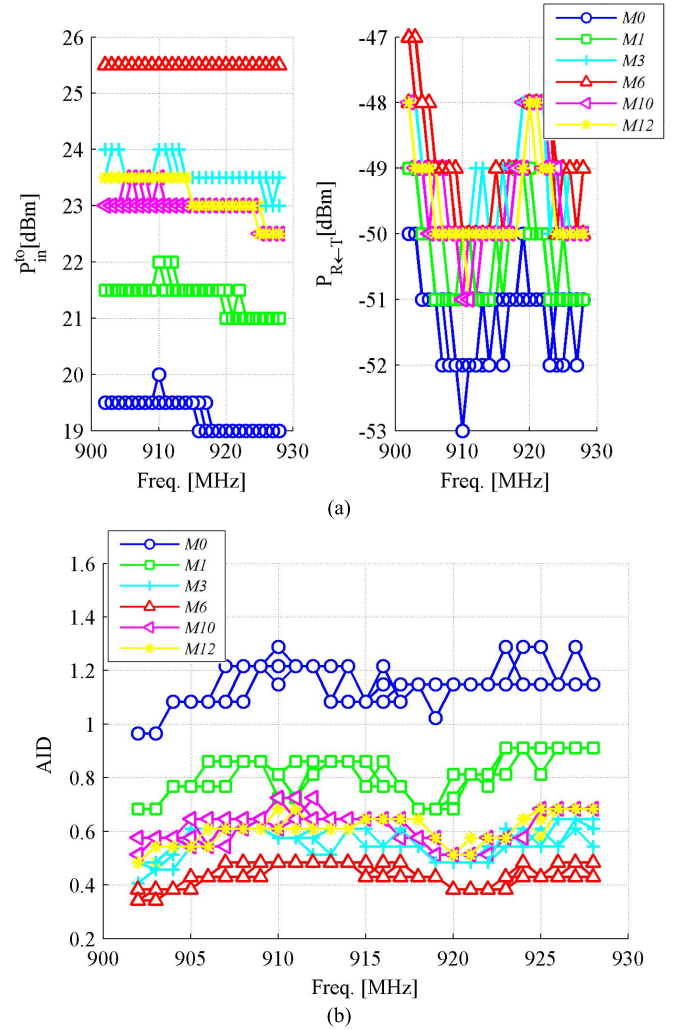


Fig. 8. Measured (a) P_{in}^{to} and $P_{R \leftarrow T}$ and (b) AIDs versus frequency in the variation of corrosion progression.

and deploying the antenna, an acceptable tradeoff between sensing (sensitivity) and communication (distance) based on UHF RFID TABS can be achieved. Based on the design, experimental studies and validation of corrosion detection and characterization are examined in section IV.

IV. MEASUREMENTS AND DISCUSSION

A. Experimental Setup

The forward and backscattered powers of the tag were measured using a ThingMagic Mercury xPRESS platform. The test setup and software flowchart of the RFID sensor system are depicted in Fig. 7. The distance between the reader and tag antennas was fixed to 1 m. The reader antenna is circularly polarized with a 6-dBi gain when the radiated power was decreased from 30 dBm in a step of 0.5 dB to find the threshold power to activate the tag (P_{in}^{to}) and corresponding backscattered power ($P_{R \leftarrow T}$), hence yielding a maximum 4-W effective isotropic radiated power. Owing to the firmware limitation, the measurement was only carried out under the operating frequency of 902–928 MHz and the reader was set to increase 1 MHz per step. The test was repeated four times for each sample for robustness.

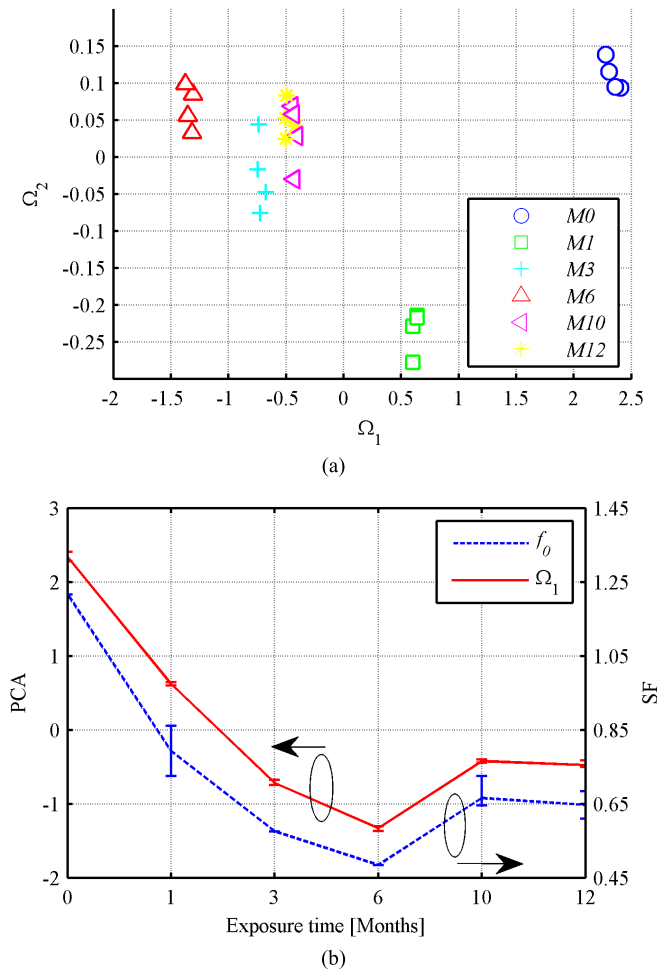


Fig. 9. (a) Distributions of Ω_1 and Ω_2 for the corrosion samples. (b) f_0 and Ω_1 versus corrosion progression. Dashed line: extracted feature using SF. Solid line: extracted feature using PCA method.

B. Results and Discussion

In order to evaluate the performance of the proposed method, a test was carried out in a typical office in the presence of tables, boxes, metallic cabinets, and other sources of clutter [49]. Fig. 8(a) shows the four times measurements of P_{in}^{to} and $P_{R \leftarrow T}$ versus frequency in the variation of samples. Comparing P_{in}^{to} with $P_{R \leftarrow T}$, we can find a significant improvement in the sensitivity for the forward power to activate tag, which can be attributed to the higher power resolution of the transmitter and power-starved property in the forward link [50] while a major limitation for the measurement of backscattered power is the resolution of analog-to-digital converter (ADC) in the receiver. Because of the lossy FR4 substrate and the limited measurement bandwidth, it is not easy to find the resonant frequency.

Fig. 9(a) shows the projection coefficients of the AIDs [shown in Fig. 8(b)] onto the PC1 and PC2, reflecting major corrosion progression, i.e., Ω_1 and Ω_2 . Since Ω_1 represents the dominant variance (more than 97%) of corrosion signatures, it is then selected as a feature for corrosion characterization. Fig. 9(b) illustrates the features extracted from PCA method and SF. We can find that the sensing variable of AID through

both of f_0 and Ω_1 can identify the corrosion progression in the early stage. However, Ω_1 demonstrates a better robustness. The corroded area becomes loose and flakes off as it expands, and this shows that later-stage corrosion will spread rather than increase in thickness [8]. That is, metal loss becomes dominant in the later stage and this explains why the abnormality incurs in the 10 and 12 months corrosion. The results are in line with the previous studies using vector network analyzer and waveguides [13]. In addition, measured with laser profilometry, the average value of corrosion layer thickness for one, three, and six months exposed corrosion samples were about 43, 77, and 108 μm , respectively [51]. Therefore, the proposed method of RFID sensor system using AID and PCA shows good agreement with the previous measurements on the dedicated samples.

Data supporting this publication is openly available under an ‘Open Data Commons Open Database License’ [52].

V. CONCLUSION

A 3-D UHF RFID tag antenna has been designed to sense the corrosion in metals. PCA has been used to extract sensing information by a sweep-frequency measurement of AID, which relieves the challenge in the antenna design, while enhances the sensitivity and robustness. The developed RFID sensor system can successfully detect and characterize the corrosion stages and remotely measure the corrosion’s information via a reader and a tag in a stand-off distance. It inherits the advantage of pulsed eddy current for NDT&E and demonstrates a cost-effective way to implement distributed monitoring. This approach has potential to bridge the gaps of NDT&E and SHM for industry application.

However, there are some limitations. The first is that one dedicated antenna is investigated for a set of dedicated samples. The second is that the RFID grid needs to be studied for distributed monitoring. Future work will focus on how to solve these limitations and improve the RFID sensor system, which includes the design and development of more antennas for different defects and samples. Different measurement strategies from readers will be further investigated as well.

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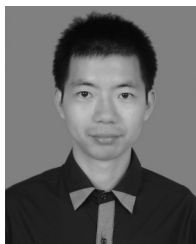
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