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Passive UHF RFID tag as a sensor for crack depths

Mugahid Omer[1,2], Gui Yun Tian[1, 3*], Bin Gao[1], Dongming Su[1]

1 School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, People's Republic of China
2 Faculty of Engineering and Technology, Nile Valley University, Atbara, Sudan
3 School of Electrical and Electronic Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom
** Corresponding author: g.y.tian@uestc.edu.cn*

***Abstract*— The use of UHF RFID passive tags for defect detection is a promising application in structural health monitoring. However, it's a challenging task while most related information to tag antenna design is not available as well it suffers from the interference effect on wireless measurements. In this article, we investigated and developed a new technique for crack depth sensing by using a passive UHF RFID tag as a sensor which interrogated by thingmagic M6e platform. Wireless power transfer WPT level and the frequency sweeping are used to match between tag impedance and metal induction effect. The distance between the tag and reader is adjusted at 30cm which can achieve high quality factor. As a result, the tag backscatter signal become rich with maximum peak components. The proposed technique called power peaks feature extraction (PPFE) which is used to detect the artificial crack depth on the surface of the stainless steel and ferromagnetic samples. Skewness is applied on PPFE to offer a direct approximation procedure for the crack depth. A linear relationship of skewness achieves high accuracy result with a maximum estimation error of 0.1 mm for stainless steel sample, the technique is validated and compared with the frequency domain result, and it achieves all most the same accuracy for the stainless steel sample.**

***Index Terms*—passive RFID tag, crack depth, skewness.**

I. INTRODUCTION

The Small cracks appear on the metal material surface, or deep inside defiantly affect the performance of the mechanical structure. The growth of the crack leads to decay system performance or to complete damage of the material which it may cause a severe disaster if it is not detected in earlier time. Health monitoring and non-destructive testing (NDT) systems were emerged to give a real-time report of the monitored system without disturbance of the system operation [1]. Radio frequency identification (RFID) system provides an alternative solution for wireless sensing and real-time health monitoring. RFID system is composed of reader and tag. The tag is composed of antenna and radio frequency integrated circuit RFIC. The tag scavenges its operating power from the reader interrogation signal. The backscatter signal from the tag includes a tag electronic product code (EPC) unique identifier and some measurable parameters such as received signal strength (RSSI) and phase.

Nowadays, RFID systems have been widely used in many areas and have been developed for use in the area of sensor system [2]. RFID system is classified into three groups due to operating frequency, low-frequency LF, high-frequency HF, and ultrahigh frequency UHF. Later UHF RFID is the most popular used when it is compared with LF and HF RFID

systems because of its far distance reading range up to ten meters [3], and it could be deployed to form a monitoring WSNs. The disadvantage of using UHF RFID signals it cannot penetrate to detect defect inside material while other frequency ranges of RFID were used for that purpose [4].

The challenges of using on metal mounted UHF RFID tag for defect sense, rely on the change of the tag antenna specification due to the change of the tagged object material. The use of tag antenna sensing capability is divided into two categories direct and indirect measurement strategies [1][2]. The direct strategy may include tag turn on power [5], backscattered power [6], and phase [7]. The indirect strategy may include radar cross section (RCS) [8], an analog identifier (AID) [3], and an in-phase/quadrature IQ signal based sensing [4]. The indirect measurement strategy may need additional hardware for investigation or need more information about the tag antenna specifications like antenna impedance, chip impedance, and chip activation power. Most often, not all of this information is available in vendor datasheet. Therefore, researchers deal to use their own designed tag when they use it as a sensor. Commercial tags unavailable information's and the limitation of the harvested power level and the attenuation of the transmitted signal make the use of a passive antenna for defect detection remains a challenge. However, regarding the use of the passive tag, researchers are developing various techniques for defect detection like strain [9][10][11], cracks [6][12][13], and corrosion [3][14][15]. The limitation of the techniques used for crack detection either it used short communication range like LF or HF, nor it can detect the cracks that directly persist on tag antenna instead of the cracks that occur in the monitored substances.

The contribution of the proposed article can be drawn from its ability to detect the under tag crack depth by using UHF reader platform, while most of the similar research focus on designing tags for sensing [3], or they may use high-cost apparatus such as vector network analyzer (VNA) [14].

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Alternatively, a new reliable methodology is used, which we call it power peak feature extraction (PPFE), and it achieves high accuracy result with a direct relationship between the crack depth increment and the change of the skewness function when compared with the accuracy achieved in [7][16].

II. UHF RFID TAG SENSING METHODOLOGY

Researchers investigated the use of RFID systems for defect detection and characterization for many reasons related to tag features such as low cost, small profile, has a unique identifier, easy to deploy in a wide area and remotely accessible. These features, encourage researchers to propose a potential use of tags as a distributed sensor network. Fig. 1 illustrates the sensing mechanism and potential applications.

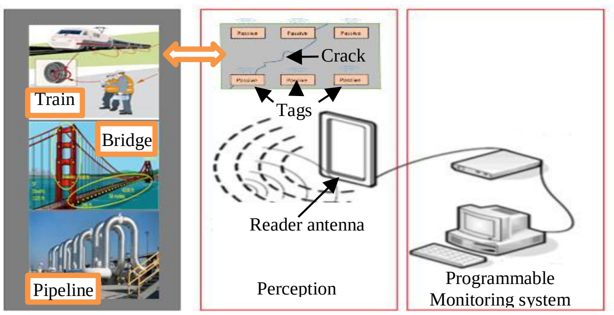

Fig. 1. Potential Distribution of passive RFID tag sensor network for defect detection.

This article focuses on the study of detecting under tag surface crack and the corresponding impact due to the increment of the crack depth. However, to implement the sensing technique, the power level is swept gradually, and the received signal is analyzed to detect the crack and follow up the changes of the crack depth.

A. RFID tag signal capturing principle

Backscatter signal from tag has different information such as tag ID, RSSI, frequency, and phase. This information is extracted to identify, track, and sensing. Many strategies are followed to implement the desired target. Therefore, to achieve the target of this article, a sweeping power technique is used. In more details, for each value of the frequency band (902–928MHz) the transmitter power is increased until the tag receives sufficient power to activate the chip. Thus, as a result, the tag backscatter the signal to the reader which start to record all information corresponding to the received signal. In turn, the similar scenario is repeated for the new frequency.

Charge pump rectifier circuit, which is used to provide DC power to RFIC, produces more efficient power at different peaks level of power optimization waveform POW when it is compared with continues wave (CW) form [17]. As well it seems like, pulse eddy current which it can reduce environmental interference and increase transient response measurement sensitivity [18]. In our case, the reliability of RSSI measurement is increased. The conducting and magnetizing properties of objects could be characterized by transient response [19]. Therefore, all of this information inspiring to infer a new technique depending on power peaks. The transient response of power peaks are used to detect the defect of the material while tag is frequency and power dependent.

Maximum wireless power transfer (WPT) between tag and reader is affected by the tag quality factor, which it is frequency dependent. Equation (1) represents the quality factor without metallic object effect [20]

$$Q = \frac{2\pi f_r L_{Tag}}{R_{Tag}} \tag{1}$$

Where L_{tag} and R_{tag} refer to tag inductance and resistance respectively. When the tag attached with a metallic object, the mutual inductance between the tag and object should be considered, and it could be represented by metal equivalent resistance and inductance R and L respectively. The resistance R depends inversely on metal conductivity and, L depends on metal permeability, where both R and L depend on the eddy current path. To simplify the effect of the metal attached or placed near the tag, only the metal inductance effects could be added in parallel with the tag circuit as shown in Fig. 2.

The new technique is called power peaks feature extraction PPFE which it focuses on the peak points of the received power. The proposed technique claims that the dominant extracted features are accompanied with the transient response of the peak points which can achieve high quality factor due to impedance matching. The crack changes the induction behavior of the metallic materials. on-object antenna impedance can achieve both maximum radiation and chip impedance matching due to power and frequency sweeping [1] as shown in equivalent circuit Fig. 2.

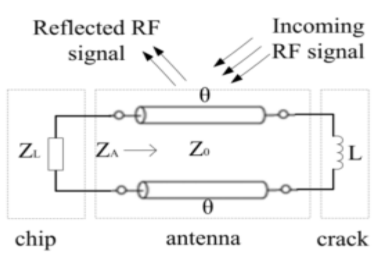

Fig. 2. The equivalent circuit for the tag attached to a metallic object

The PPFE technique is applied in the time domain, then it validated with the frequency domain analysis, and it achieves high accuracy for under tag crack detection. One of the advantages of the proposed testing techniques, only the reader system is used for testing, and there is no need for more additional apparatus. As well, all measurements are independent of tag unknown parameters; these features will expand the use of the commercial UHF RFID tags for defect

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sensing. The concept and implementation of PPFE are described in more details in section C.

B. RFID response and feature extraction for crack characterization

RFID and PEC have the same behavior when they respond to the pulsed signal. The signal which contains multiple frequencies has different penetration depth capabilities. The direct relationship between the frequency and the penetration depth δ on the metallic material described in equation (2)

$$\delta = 1 / \sqrt{\pi f \sigma \mu} \tag{2}$$

Where f is the pulsed signal frequency, σ and μ represent the conductivity and permeability of the material. It's obvious from equation (2) that the skin depth has inversed relationship with the frequency. as well the defects of the material can effect on conductivity and permeability. Extensive studies have been proposed to observe the change of material conductivity and permeability over the corroded layer [20][21]. Same like corrosion, cracks can be detected by exposing the material to different frequency components and then, extract the features that effected due to conductivity and permeability changes. The change of signal penetration depth accompanied with the change of material properties which caused as a result of defect persistence, lead to extract different features like signal maximum peak value, change of peaks during a period of time, and the difference between the maximum and a minimum peak of the signal. After the implementation of the PPFE technique, we observe that the increment of the under tag crack depth makes the stainless steel sample behave like the healthy ferromagnetic sample and vice versa.

C. PPFE Implementation in the time domain

The PPFE is applied to the RSSI signal which is represented in the time domain. The main idea behind the PPFE is to extract and monitor the health status of the under tag material in a novel and straightforward relationship. A set of steps should be followed

i. The interrogation reader code sequence is shown in table 1.

TABLE 1.
READER PSEUDO CODE.

```
while(1) {
For frequency = 902 :  step 0.5 : 928
    For power= 5: step 0. 5:  30
    Reader sent request
       If tag respond
           Save the received data
           Exit power loop
       End if
   Next power
Next frequency
}
```

ii. The received data for 500 seconds is saved and is analyzed in Matlab

iii. The total period is divided into short interval periods, the length of the short period T is calculated as shown in Eq. (1).

$$T = T_{FP} - T_{FR} \tag{3}$$

Where T_{FP} is the time for the first peak, and T_{FR} is the time for the first response. The transient response of the peaks is calculated within each period of time T, which could be defined as the count of peaks per each period time T. This feature used to detect the variation of the crack depth. Fig.3 shows the representation of T period in the received signal graph.

iv. Number of peaks is calculated for each interval time T

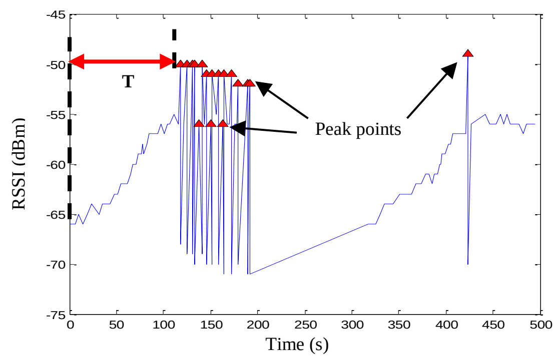

Fig. 3. Representation of the period time T on the received power signal.

D. Skewness feature extraction for PPFE

The skewness feature is used to test the bias of the PPFE readings for each one of the test samples. The main role of this statistical feature is to evaluate asymmetry of the data [4]. For a set of data X, the skewness feature is given by Eq. (2).

$$\gamma = \mathbf{E}\left(\frac{X - m}{SD}\right)^3 \tag{4}$$

Where X is the data, m is the mean; SD is the standard deviation. The skewness has zero value for the normally distributed data. A negative value or positive value for the skewness indicates that the left tail has long relative to the right tail and vice versa.

III. EXPERIMENTAL SETUP

A specimen of a ferromagnetic sample is 140×60×10mm, and a sample of stainless steel is 120 × 60 × 5mm are shown in Fig. 4. These samples attached with the RFID tag for crack detection. The ferromagnetic sample has four artificial cracks with 8 × 0.2 mm for length and width respectively, while it is prepared with different depths 8, 8.5,9 and 9.5mm. The stainless steel sample has three artificial cracks prepared with similar length and width 13 × 0.5 mm respectively and with different depth 0.5, 1 and 1.3mm. The samples are tested from 30cm far from the reader by using the Thingmagic M6e platform with 6 dBi reader antenna gain to monitor and observe the changes in the received signal. The received signal from healthy and cracked sample is analyzed in the frequency domain and time domain. The maximum reading distance for the tag to respond is 40cm for the healthy samples and 35cm for the cracked samples.

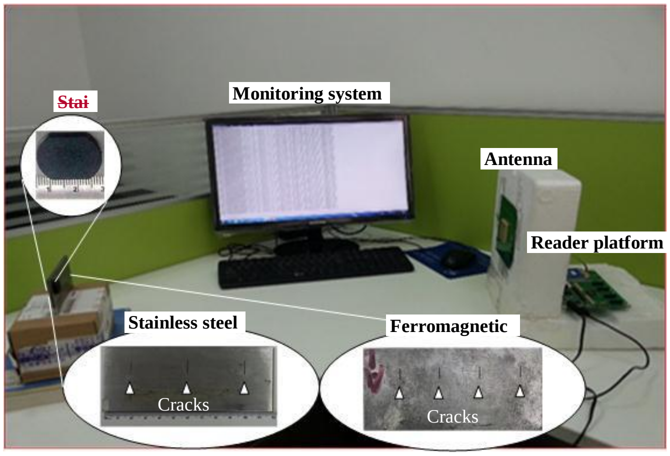

Fig. 4. Reader measurement platform and the sample under test.

IV. Results and Discussion

A. Time domain analysis for stainless steel

The received signal peaks distribution, as shown in Fig. 5, 6, 7, and 8, have clear differences. Healthy sample as shown in Fig. 5 has no peaks because the height difference between the adjacent peaks is not sufficient to pass the threshold value, which it has been adjusted to be at least more than two. Thus, the period T as defined in Eq. (1) devolves to zero and the corresponding bar plot will be zero. Fig. 6 and Fig. 7 show the received signal for the cracked sample with 0.5 mm, 1 mm and 1.3 mm, respectively. Fig. 6 represents the received signal with the maximum peaks while Fig .7 represents the peak counts in each period T. If the existence of peaks within the period, is represented by hit state, and the absence of peaks within T period represented by miss state. Therefore, all crack states for stainless steel as shown in the bar plot of Fig. 7, could be encoded in the form of [hit miss hit], while for healthy sample only miss state is available. These features could be used to distinguish between healthy and cracked sample also it could be coded in binary form.

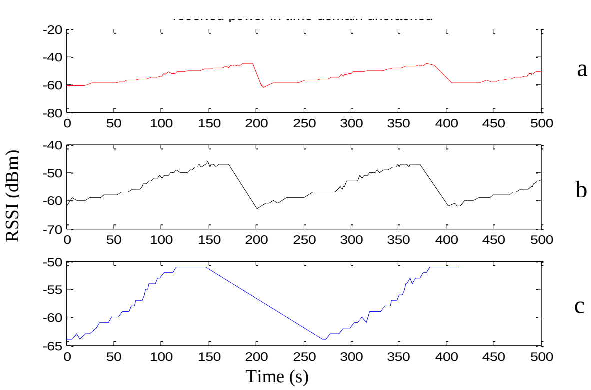

Fig. 5. Received power signal for the stainless steel healthy sample measured from different distances (a) 30 cm far from the reader (b) 35 cm far from the reader (c) 40 cm far from the reader.

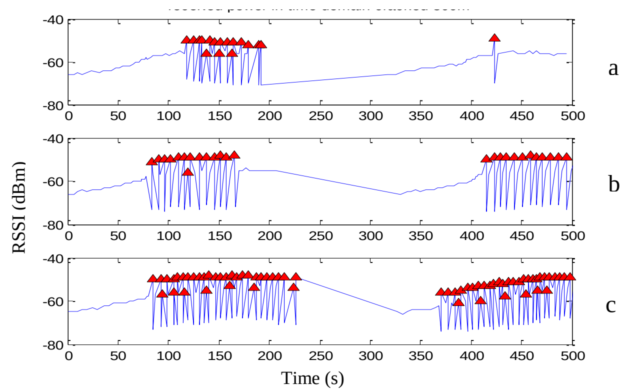

Fig. 6. Received power signal for stainless steel cracked samples measured from 30 cm (a) 0.5 mm crack depth (b) 1 mm crack depth (c) 1.3 mm crack depth.

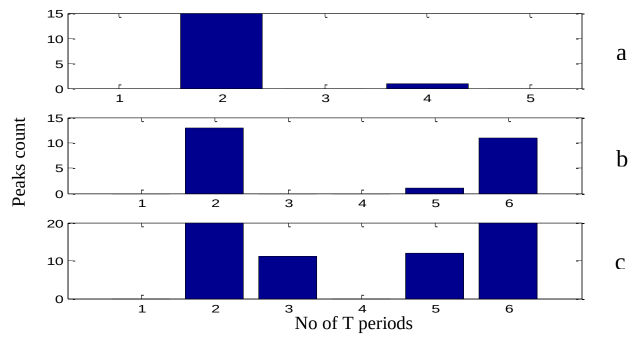

Fig. 7. Peaks count extracted from the received power at each T interval time for stainless steel cracked samples measured from 30 cm (a) 0.5 mm crack depth (b) 1 mm crack depth (c) 1.3 mm crack depth.

After crack detection, it is required to go deep and derive a relationship between the number of peaks and crack depth estimation; Skewness is used to build this relationship. Therefore, as shown in Fig.7, when the crack depth is increased the skewness is decreased as shown in Eq. (3).

$$sk \propto \frac{1}{c_d} \tag{5}$$

Where sk is the skewness for the extracted power peaks, the cd is the crack depth. In Fig. 7.b, this linear curve fitting has a maximum error of 0.1mm; this means the crack depth estimation is achieved by a simple and direct linear relationship. This relationship is affected by the separation distance between reader and test sample.

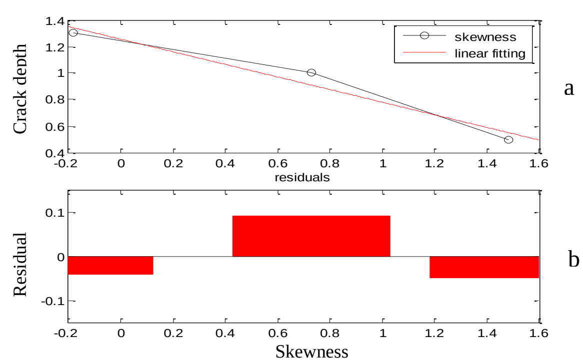

Fig. 8. The skewness for different crack depth on stainless steel (a) skewness with the curve fitting (b) residuals.

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To test the occurrence of the peaks phenomenon even if the measurement distance is changed. The cracked stainless steel sample tested from 35cm, and the received signal is shown in Fig. 9, where Fig. 10 represents PPFE of the received signal.

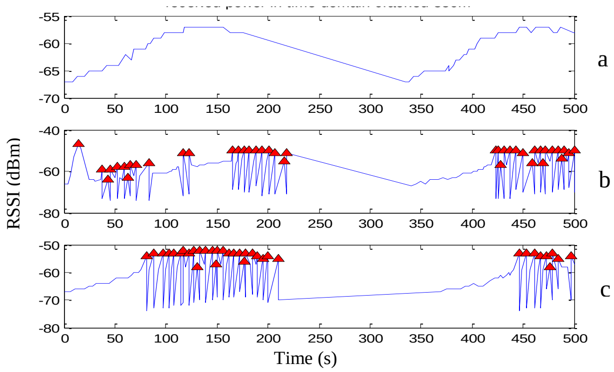

Fig. 9. Received power signal for stainless steel cracked samples measured from 35 cm (a) 0.5 mm crack depth (b) 1 mm crack depth (c) 1.3 mm crack depth.

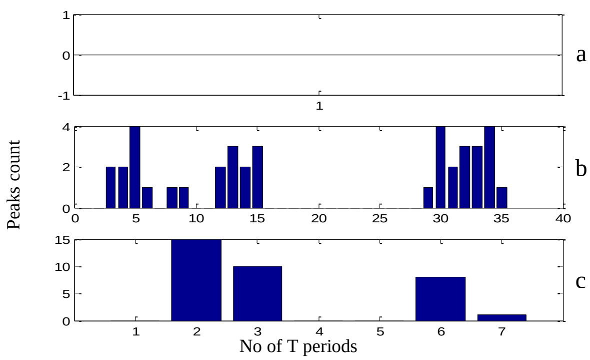

Fig. 10. A number of peaks extracted from the received power at each T interval time for stainless steel cracked samples measured from 35 cm (a) 0.5 mm crack depth (b) 1 mm crack depth (c) 1.3 mm crack depth.

It is obvious from Fig. 9.a the signal is increased and decreased gradually without making any variation in high peaks as a result in Fig. 10.a the number of peaks is zero which mean the small depth cracks could not be detected at the maximum reading distance, In other words, the change of the separating distance between the test sample and the reader affects the under tag material behavior. Thus, the separating distance 30cm give a good match to detect small crack depth for the on-object tag.

B. *Time domain analysis for ferromagnetic sample*

The distribution of the received signal peaks is shown in Fig.11. It consists of clear differences. Healthy sample as shown in Fig. 11.a, and cracked sample as shown in Fig. 11.e, they have clear peaks. While Fig. 11.b, Fig. 11.c and Fig. 11.d, have smooth curves. Thus, the technique PPFE could not be used in this case because it has no enough peaks to be linked with the skewness function to fit a direct relationship.

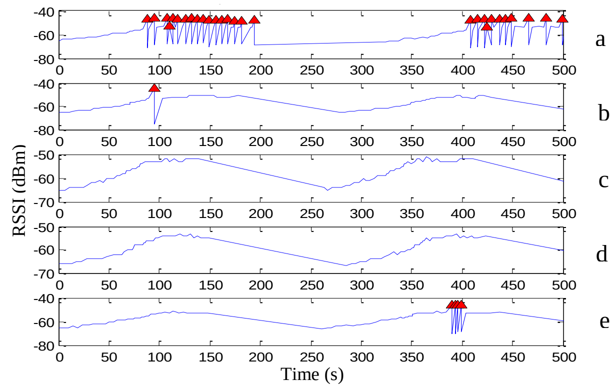

Fig. 11. Received power signal from ferromagnetic sample measured from 30cm (a) healthy sample (b) 8mm crack depth (c) 8.5mm crack depth (d) 9mm crack depth (e) 9.5mm crack depth.

C. *Frequency domain analysis for stainless steel sample*

The received signal and the transmitted power are measured three times for each frequency within the range 902–928 MHz with the capturing procedure illustrated in table 1. The average value of the transmitted power and the ratio of the (received power/transmitted power) are shown in Fig. 12 and Fig. 13, respectively.

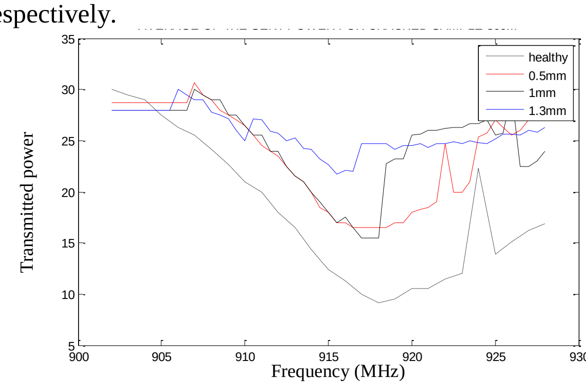

Fig. 12. Transmitted power for stainless steel sample.

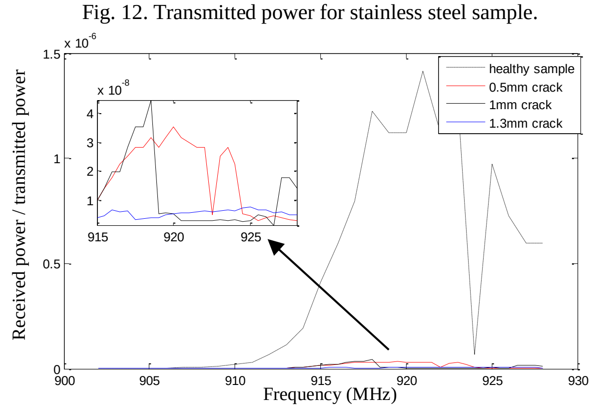

Fig. 13. (Received power/transmitted power) signal ratio for stainless steel sample.

Healthy sample signal, as shown in Fig. 12 and Fig. 13, has an obvious difference compared with the cracked sample. Thus, to create a linear relationship for crack depth estimation, the mean (m) of the (received power/ transmitted power) is calculated in Eq. 4.

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$$m = \frac{1}{N}\sum_{f=902}^{928}\left(\frac{RP_f}{TP_f}\right) \tag{6}$$

Where N represents the frequency bandwidth within range (902-928MHz) and it equals 27, f is the frequency, RP_f and TP_f represent the received power and the transmitted power respectively. Fig 14.a shows the inverse relationship between the crack depth and the mean when the mean is decreased it indicates that the crack depth is increased. A linear curve fitting is used for direct relationship estimation as shown in Fig. 14.a and the residual error is shown in Fig 14.b

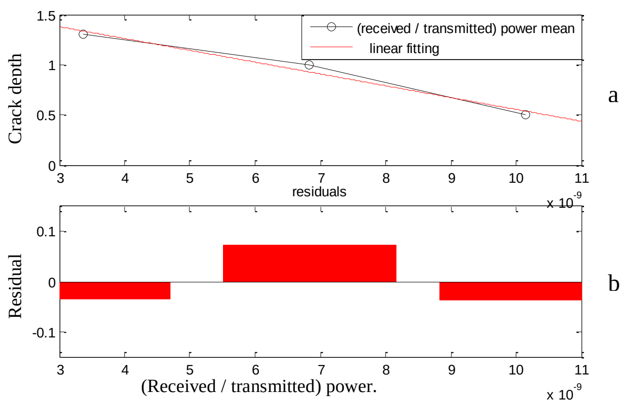

Fig. 14. The mean of (received power / transmitted power) for different crack depth on stainless steel (a) the mean with the curve fitting (b) residuals

From Fig. 14.b, the maximum estimation error is less than 0.1mm. From Fig. 13 we can observe the big difference of (received power/transmitted power) of the healthy sample when compared with the cracked sample due to the occurrence of small cracks on the surface of stainless steel.

D. Frequency domain analysis for the ferromagnetic sample.

The ferromagnetic sample is analyzed in the frequency domain to observe the change of the signal due to crack depth change. Fig. 15 shows the transmitted power level where the healthy sample has a clear difference in power level at a frequency range (920 - 928MHz), while the cracked sample signals are converged and are overlapped in most points in the frequency range.

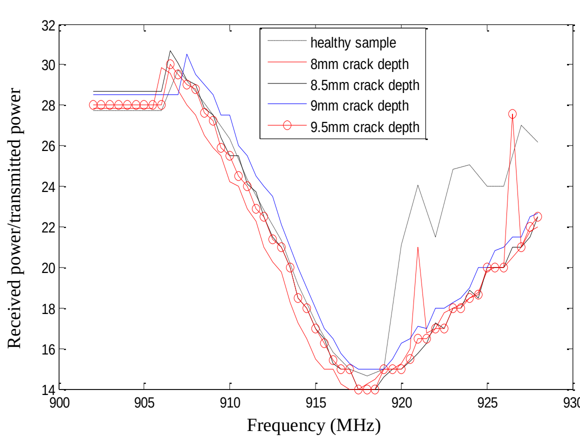

Fig. 15. Transmitted power for the ferromagnetic sample.

For more investigations, Fig. 16 illustrates the ratio of (received power/ transmitted power) signal, and it is obvious there is a clear difference between the signal level for the cracked sample. Therefore, it can give a good estimation for the crack depth as the crack depth increases the power level decrease for the crack depth ranged between 8mm and 9mm, but the crack depth 9.5mm do not follow the same sequence, and it converges to the power level of the crack depth 8.5mm.

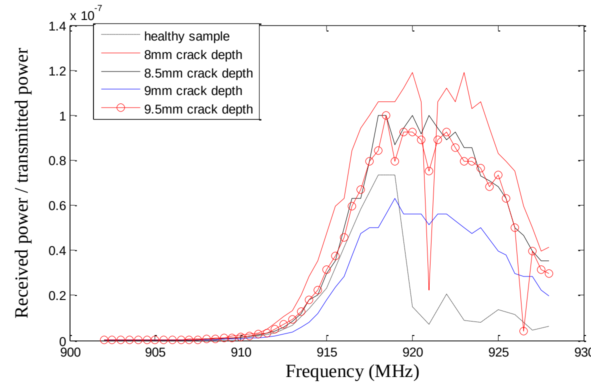

Fig. 16. The ratio of (Received power/transmitted power) for the ferromagnetic sample.

To make a linear relationship, the mean of the (received power/transmitted power) ratio for all frequency range collaborate with linear curve fitting as shown in Fig. 16.

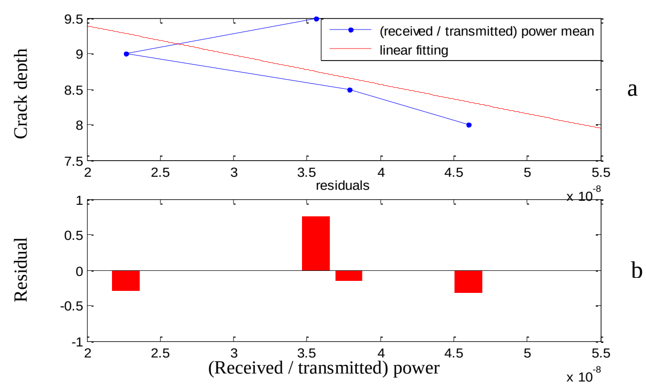

Fig. 17. The mean of (received power / transmitted power) for different crack depth on the ferromagnetic sample (a) the mean with the curve fitting (b) residuals

The relationship between the mean and the crack depth is linear for three cracks in between 8mm and 9mm, while the 9.5mm crack has anomaly mean. Despite the presence of anomalies, but still, the maximum residual error approximately equals 0.8mm as shown in Fig. 17.

V. CONCLUSION AND FUTURE WORK

Under tag crack depth sensing is investigated by using UHF RFID Thingmagic platform and the new technique is applied in two different materials stainless steel and ferromagnetic. PPFE is applied in the time domain of the received signal, and it achieves high accuracy result when it collaborates with skewness linear curve which it gives maximum estimation error about 0.1mm for the stainless steel. This result is validated by frequency domain analysis, and it gives almost the same result when the mean of (received power / transmitted power) calibrated with the linear curve. The PPFE technique had a less accurate result when it applied to the ferromagnetic sample where there are no peaks appear for the crack depth ranged between 8mm and 9mm. For more investigations, the mean of (received power/transmitted power) calibrated with the linear curve, and it gives good result about 0.8mm for the maximum error. As a result, PPFE could be used for under tag crack detection and estimation with high accuracy result for the stainless steel which prepared with short depth artificial cracks ranged between 0.5 to 1.3mm. Although, PPFE has a less accurate result when it is used for ferromagnetic material which prepared with long depth artificial cracks ranged between 8 to 8.5 mm. However, still, the frequency domain analysis could be used for under tag crack detection with less accuracy approximately 0.8mm for maximum residual error. PPFE depends only on the peak values. Thus, it could be applied to reduce the data size of the structural health monitoring SHM and IoT systems. In the future work, we can investigate the reliability of using this technique for crack localization and crack length and depth estimation.

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Mugahid Omer received the B.Sc. degree in electrical and electronics engineering from Nile Valley University, Atbara, Sudan, in 2000, and the M.Sc. degree in electronics (Computer Engineering) from Sudan University of Science and Technology, Khartoum, Sudan, in 2005. He is currently pursuing the Ph.D. degree in School of Automation Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu, China. His research interests include sensor signal processing, wireless sensors networks, Radio Frequency Identification (RFID) and the internet of things (IoT).

Gui Yun Tian (M'01–SM'03) received his B.Sc. degree and M.Sc. degree from University of Sichuan, Chengdu, China in 1985 and 1988, respectively, and Ph.D. from University of Derby, Derby, U.K., in 1998. He is currently the Chair Professor of Sensor Technologies at School of Engineering, Newcastle University, Newcastle upon Tyne, U.K. He is also an adjunct professor in the University of Electronic Science and Technology of China. His main research interests include electromagnetic sensors, sensor array and sensor network, electromagnetic non-destructive evaluation, advanced signal processing and integrative systems and applications. He has coordinated several research projects from the Engineering and Physical Sciences Research Council (EPSRC), Royal Academy of Engineering and FP7. Also, he has good collaboration with leading industrial companies such as Airbus, Rolls Royce, BP, nPower, Network Rail and TWI among others.

Bin Gao (M' 12-SM' 14) received his B.Sc. degree in communications and signal processing from Southwest Jiao Tong University (2001-2005), China, M.Sc. degree in communications and signal processing with Distinction (2006-2007) and a Ph.D. degree from Newcastle University, UK (2007-2011). He worked as a Research Associate (2011-2013) with the same university on wearable acoustic sensor technology. Currently, he is a Professor with the School of Automation Engineering, University of Electronic Science and Technology of China (UESTC), China. His research interests include sensor signal processing, machine learning, social signal processing, nondestructive testing and evaluation where he actively publishes in these areas. He has published over 60 papers on these topics on various journals and international conference proceedings. He has coordinated several research projects from National Natural Science Foundation of China

Dongming Su received the B.Sc. Degree in Chongqing University of Posts and Telecommunications (CQUPT) in 2016. He is currently studying for M.Sc. degree of Automatic instrumentation engineering in University of Electronic Science and Technology of China (UESTC). His main research interests include Radio Frequency Identification (RFID), sensor array, sensor network.