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IQ Detection based RFID Sensors for Corrosion and Crack Characterisation

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Abstract

Radio frequency identification (RFID) sensor systems have unique advantages of identification, communication and sensing together. Previous researches on RFID based sensing investigate power based features, and face the challenge of low sensitivity and robustness due to environment RF field. In this paper, rather than using received signal strength indicator (RSSI), we present a method using features of transient responses from in-phase quadrature (IQ) signals to overcome the challenges of sensitivity and robustness in ultra-high frequency (UHF) RFID sensor systems. The transient responses of the IQ signal are analysed using skewness feature for different defects. The experimental results show that IQ based skewness features from IQ signal improve sensitivity and robustness for defect characterisation compared with previous RSSI and RCS methods.

Keywords: RFID, in-phase quadrature (IQ), transient response, skewness.

1. Introduction

Corrosion and cracks are critical issues of metal infrastructures impacting the health status and mechanical performance of the structure, jeopardising safety with failure of metallic structures. Constant inspection and monitoring is important to detect and prevent potential structural problems [1]. Non-destructive testing (NDT) methods are developed for in-lab detection of infrastructures without causing damage. Structural health monitoring (SHM) aims to achieve damage detection and characterisation in real time to monitoring the health status. With the advantages of wireless, fully passive, low cost and robustness as in-situ sensors, radio frequency identification (RFID) sensing systems is receiving more and more attention to bridge the gap between NDT and SHM applications [2].

Based on operation frequency, the RFID technology can be categorised into three types, namely, low frequency (LF), high frequency (HF) and ultra-high frequency (UHF). LF RFID has advantage of higher penetration depth as a result of low operation frequency, its communication distance is up to 5 cm which is limited by the magnetic coupling [3]. HF RFID has lower sensitivity of in-depth defects compared with LF, but the communication distance is increased to 10cm [4]. Passive UHF RFID has communication range of up to ten metres and can achieve sensing for surface defects with dedicated designed sensors [5]. With the long communication distance, UHF RFID sensors can be massively deployed to form sensing network for SHM application.

RFID technology is a passive wireless communication technology based on backscattering theory. An RFID system consists of a reader and a tag. The tag receives power from reader and modulate backscattered signal with impedance change. The reader then demodulates the backscattered signal to get the unique ID of the tag. In this process, not only the tag ID is recognised, but also the characteristics of the tag, e.g. impedance. RFID based sensing is based on impedance change of tag antenna due to environment effects, e.g. humidity, temperature and defects. This change is not directly measurable but can be derived from other parameters. In previous research on UHF RFID based sensing, power based features e.g. received signal strength indicator (RSSI) and radar cross section (RCS) are investigated for defect sensing and characterisation [5]. RSSI is the received power measured from reader indicating the power strength of tag signal. RCS is derived from RSSI and is robust to communication distance change. Due to environmental interference, power based features suffer from high RF level which result in low sensitivity, and slow responses from multiple sweep sampling [6]. In-phase quadrature (IQ) modulation scheme is widely used for RF communication systems, e.g. cognitive radio, IQ radar. Using features of IQ signal allows for transient changes in the magnitude and phase response of the resonator to be estimated. It can improve sensitivity for microwave resonator sensor (MRS) using single frequency detection scheme with IQ readout [7]. Amplitude and phase are two mostly investigated features of IQ signal in current studies. The phase of IQ signal has been invested for localisation of UHF RFID tags [8]. In the interferometric fibre optic sensors, the phase information of IQ signal is also investigated for sensing purpose [9]. All these researches [2] focus on static feature of IQ signal. The IQ signal is also coded signal which contains pulse. The transient behaviours can reflect the system behaviours of RFID sensor tag, communication and reader through pulse excitation.

Transient responses from pulse excitation have been investigated for non-destructive test using pulsed eddy current (PEC) method for it can reduce environmental interference and increase sensitivity [10]. Pulse-compression is introduced for SNR and defect detection capability improvement in active thermography for non-destructive evaluation (NDE) [11]. The inductive characteristics of ferromagnetic and conducting structures can be characterised using transient response analysis [12]. This concept is introduced for corrosion characterisation with LF RFID in [3] and proven to be significantly more sensitive and robust compared with static features. As sensitivity and robustness are two major issues in UHF RFID sensing system, it is worthwhile to investigate transient response feature of IQ signal for improvement of sensitivity and robustness.

The feature extraction of transient response can be performed by exploiting the characteristics of the signal such as root mean square (RMS), variance, kurtosis, skewness [13] etc. However, previous researches in RFID based sensing only focus on transient response and first order differential features, e.g. rising time, peak values of differential results, etc [3]. High order statistic features such as skewness, third order statistic feature, has advantages for quantifying transient signals' dynamic characters and shape characterisation and has been applied for many applications, e.g. barkhausen noise characterisation [14], pulsed eddy current [15], etc.

In this paper, we investigate skewness feature for characterising transient response of IQ signal to improve sensitivity of defect detection e.g. corrosion characterisation with UHF RFID tag. This paper is organised as follows. Firstly, the UHF RFID sensing system is introduced and transient response extraction of IQ signal is presented in the section 2. Then the skewness feature of transient response for IQ signal is analysed and discussed in the section 3. In section 4, the work is concluded and future direction for sensitivity improvement is given.

2. UHF RFID Sensing and IQ Extraction Method

UHF RFID based sensing system and IQ signal capturing are introduced in section 2.1. Extraction of IQ signal transient response is introduced in section 2.2. Skewness feature extraction method for transient response of IQ signal is introduced in section 2.3.

2.1 UHF RFID Sensing System and IQ Signal Capturing

An RFID sensing platform comprises RFID tag and reader, as shown in Figure 1. The communication between tag and reader hosts an asymmetric bi-directional link: the direct link from the reader to the tag and the reverse link from the tag to the reader [10]. In the former communication, the power emitted by the reader powers up the tag. Then in reverse link, the tag reflects the waves from reader and modulates backscattering signal by switching an internal impedance between two states. In this system, the tag can be used as real sensors, exploiting the clear dependence of the tag antenna's radiation characteristics on the tagged object and on the nearby environment [12]. The power based parameters, e.g. RSSI and threshold power to activate tag, are investigated for stress and defect sensing, but face the challenge of sensitivity and robustness. In addition to signal strengths and phases, IQ signal in RFID systems has analog data (before binarisation) which contains high order information, e.g. transient response feature and is investigated to improve sensitivity and robustness for corrosion sensing in this paper.

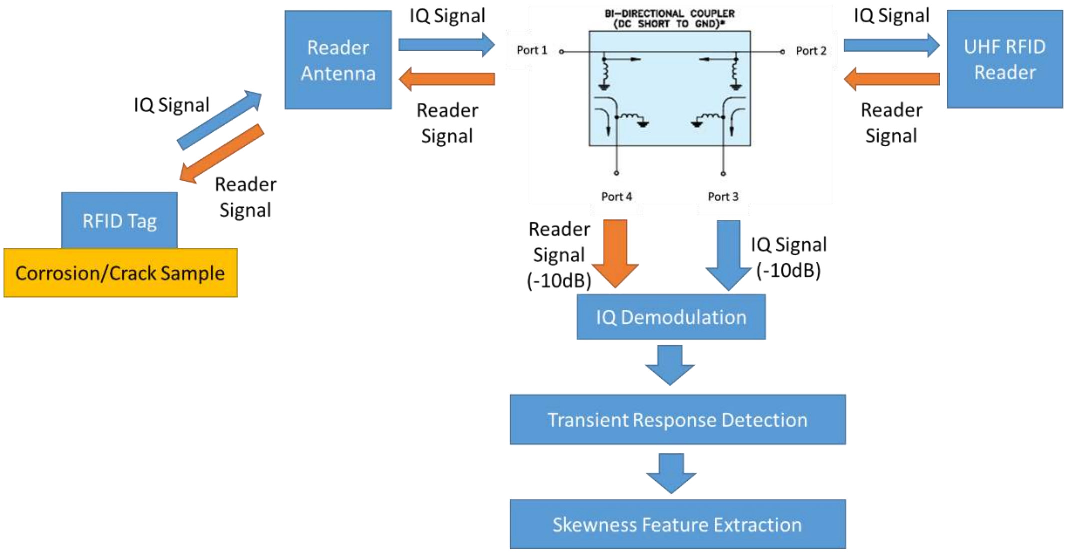


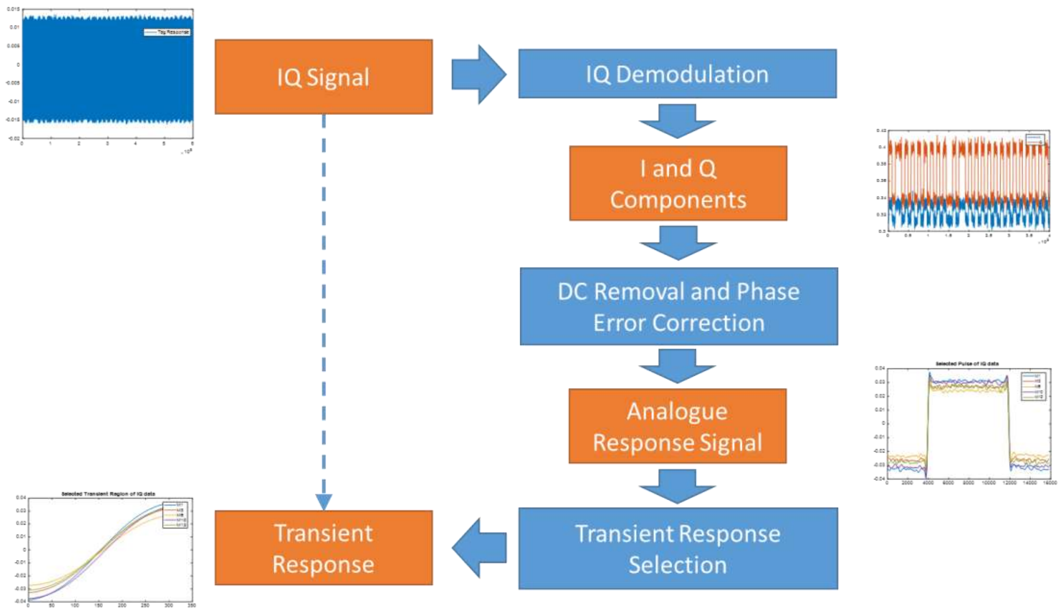
Figure 1. UHF RFID defect sensing system diagram

To capture the analogue response before binarisation in reader, a directional coupler is introduced between the reader and reader antenna to separate IQ signal and reader signal, as shown in Figure 1. The signal transmitted into Port 1 will be separate to two components, the major power goes to Port 2 and the minor power (10dB lower) is transmitted to port 4. Port 1 and Port 4 is ideally isolated. In this way, the IQ signal can be captured using an oscilloscope from output of Port 3 and the reader signal is obtained from output of Port 4.

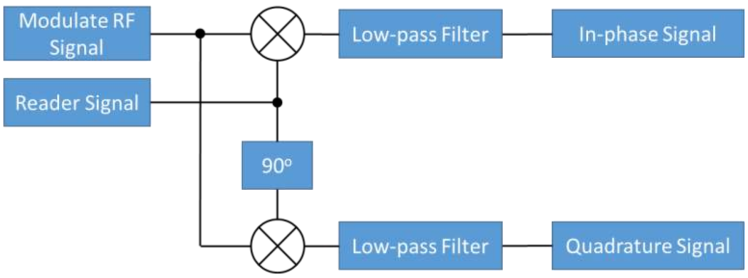
2.2 Transient Response Extraction

To extract the transient response of the IQ signal, the IQ signal is processed in three steps, as shown in Figure 2(a). Firstly, the carrier wave (CW) is removed using IQ demodulation to get analogue response data, which is a pulse shape signal. Secondly, the DC component and phase error is removed to get the analogue response signal. Then the transient response is picked from the shapes of the analogue response signals.

Obtained IQ signal and reader signal are saved and processed in Matlab to extract in-phase and quadrature signals. IQ demodulation scheme is shown in Figure 2(b). In demodulation process, the combined signal of in-phase and quadrature signals is separated to two equal parts and demodulated with two carrier waves which have same frequency but has 90° phase difference with each other. Then after a low pass filter, the I and Q components are obtained. The reader signal is used as carrier wave for demodulation in Matlab. The 90° phase shift is achieved with differential function as the carrier wave is sinusoidal wave.



(a)



(b)

Figure 2. (a) Transient feature analysis diagram and (b) I/Q demodulation diagram

The demodulated I and Q components are series of pulse-like analogue response signals for communication between tag and reader. The phase noise and amplitude noise of IQ signal is identifiable using IQ demodulation and the phase noise can be reduced using rotation matrix [16]. As DC values of IQ components I_{DC} and Q_{DC} can be computed with mean of IQ signal, we can get amplitude and phase feature by subtracting signals with I_{DC} and Q_{DC} as Eq. 2.1 and Eq. 2.2.

$$Amplitude = \sqrt{\left(I_{tag} - I_{DC}\right)^2 + \left(Q_{tag} - Q_{DC}\right)^2}\frac{I_{tag}Q_{tag}}{|I_{tag}Q_{tag}|} \qquad \text{(Eq.2.1)}$$

$$Phase = arcsin\left(\frac{I_{tag}}{Amplitude}\right) \quad \text{(Eq. 2.2)}$$

The DC component is removed and the amplitude and phase of IQ signal are identified with probability density plot of I and Q components. The data set is then rotated to X axis with the calculated phase to remove phase error and get the analogue response signal. The transient responses are selected from the analogue signals for defect feature extraction in the section 2.3.

2.3 Skewness Feature of Transient Response

After transient response of IQ signal is extracted, the skewness feature is investigated for defect sensing and characterisation. Skewness is a measure of the asymmetry [17] of the transient responses as feature extraction for corrosion stage characterisation. For a data set X, the skewness γ is defined as Eq. 2.3.

$$\gamma = E\left(\frac{X-\mu}{\sigma}\right)^3 \quad \text{(Eq. 2.3)}$$

where μ is mean of X and σ is standard derivation of X. Skewness has advantage in processing transient response and extracting high order feature. In transient response of IQ signal, the skewness feature reflects asymmetry of probability distribution of transient response. The skewness for a normal distribution is zero, and any symmetric data should have a skewness near zero. Negative values for the skewness indicate data that are skewed left and positive values for the skewness indicate data that are skewed right. By skewed left, we mean that the left tail is long relative to the right tail. Similarly, skewed right means that the right tail is long relative to the left tail. If the data are multi-modal, then this may affect the sign of the skewness. The skewness feature of IQ transient region is investigated for corrosion characterisation in the experiment validation.

3. Transient Feature Extraction Results and Discussion

The experimental validation for skewness feature of IQ transient response is undertaken with dedicated corrosion samples and compared with resonant frequency feature based on RSSI first. Then this method is applied for crack sensing and compared with IQ amplitude results for validation. In contrast to RSSI of signal power (amplitudes), IQ signal captures transient responses of the RF signal transmission. It can provide not only transmitted data but also the behaviour of sensing in RFID tag and communication behaviours. We apply the IQ signal for corrosion sensing and communication. Then the robustness of IQ demodulation transient feature is tested for lift-up tolerance. At last, the skewness feature for transient response of IQ signal is tested and validated for natural short fatigue crack sensing.

3.1 Sample Preparation and Experiment Setup for Corrosion and Crack Testing

Five pieces dedicated corrosion samples, as illustrated in the Figure 3, are produced by International Paint for investigation. They are made from mild steel S275 with dimensions of 300 mm × 150 mm × 3 mm. The samples are covered with protective layer but open the center area of 30mm × 30mm before exposing in marine atmosphere for specific time (1, 3, 6, 10 and 12 month) period of corrosion, which present as samples M1, M3, M6, M10 and M12. After corrosion at specific periods are well developed, the samples are covered with insulation paint of approximate 100 µm to preserve corrosion status. The distance between reader and tag antennas is set to 15cm to get proper signal strength for capturing IQ signal from the oscilloscope. Then the distance is reduced to 10cm to test the robustness of the skewness feature.

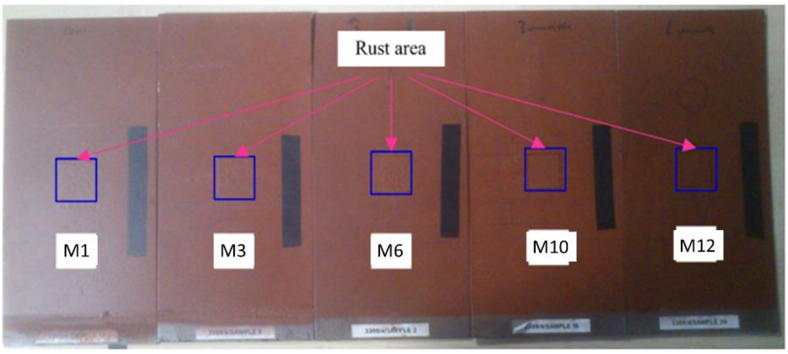


Figure 3. Corrosion Samples

To further investigate the UHF RFID sensing system and skewness feature of IQ transient response, the natural crack sample is investigated. The natural crack sample and experiment setup is depicted in Figure 4. The natural crack sample is an aluminium sample of dimensions of 160 mm × 40 mm × 20 mm with a fatigue crack of 10mm. The distance between reader and tag antennas is set to 3cm. The requisition signal frequency from reader is controlled to 905MHz and the power 30dB. The positions P1 to P5 defines five testing positions with step size of 5mm where the tag is placed during the test. P3 is the centre of the sample at the cracked surface and the natural crack is near P3, as presented in yellow box.

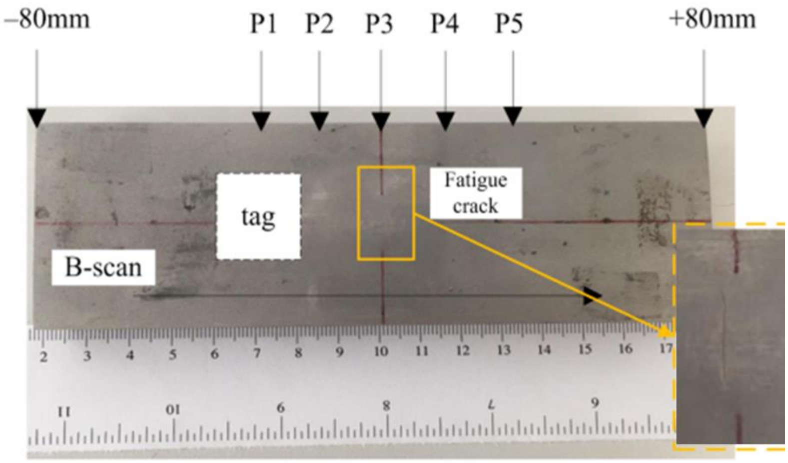
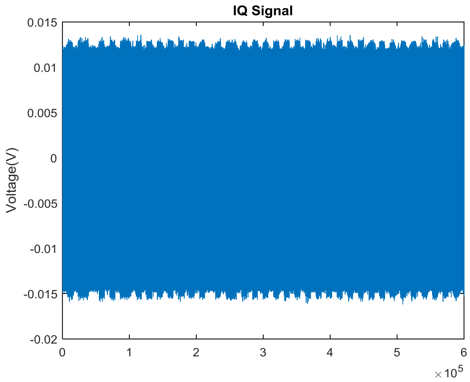


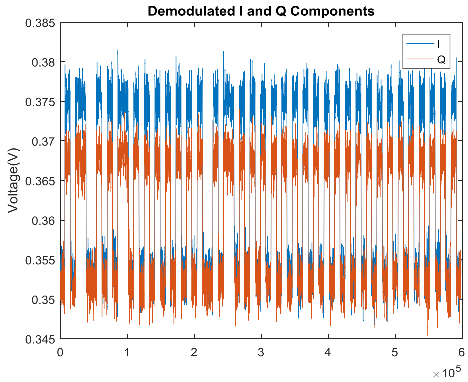
Figure 4. Natural Crack Samples

3.2 IQ Demodulation Results and Discussion

To get transient response from the experiment results, the data are processed as follows. Firstly, the raw data as shown in Figure 5(a) is multiplied with local oscillator, then filtered to base band signal, as shown in Figure 5(b). Then the DC values of the IQ components are removed and the probability density of amplitude and phase are calculated as Figure 5(c). The amplitude and phase of IQ signal are calculated from the probability density graph. Then the signal is rotated clockwise by the value of calculated phase to remove phase error. Then the analogue response signal is achieved as shown in Figure 5(d). Then the transient region of the analogue response signal is selected from each pulse. The pulse rising edge is identified using peak point of differential results and the region size is selected as 600 samples to cover the transient region, as shown in Figure 5(e).



(a)



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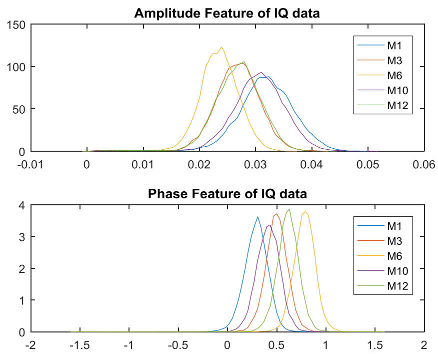
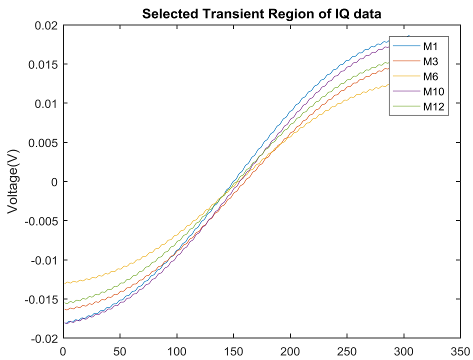


(c)

(d)



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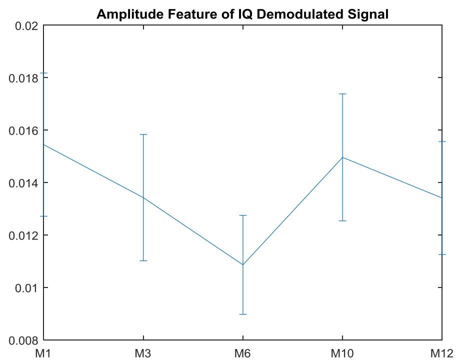
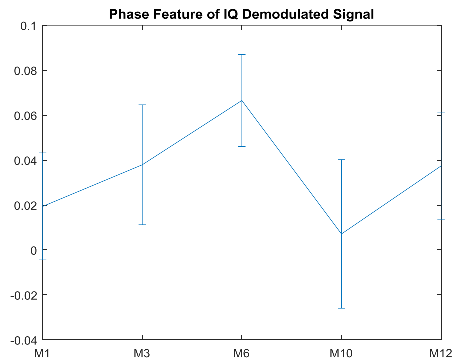


(f)



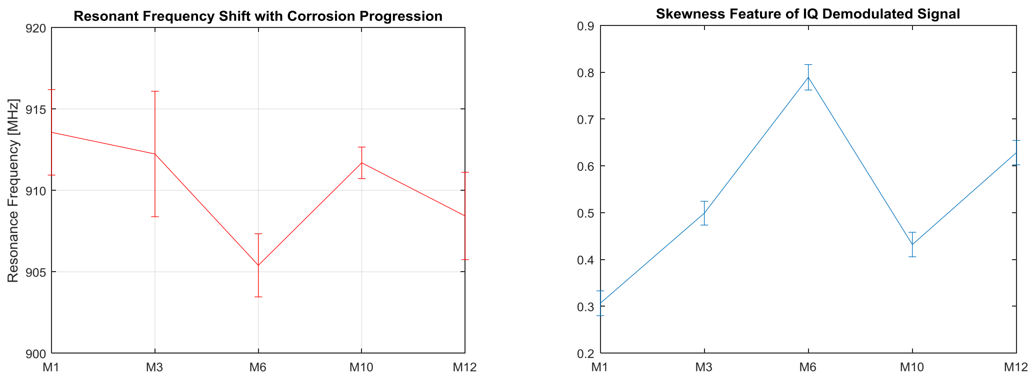
(g)

Figure 5. (a) IQ signal (b) demodulated IQ signal (c) amplitude and phase probability density of IQ signal (d) analogue response signal (e) transient response (f) amplitude feature of IQ demodulated signal (g) phase feature of IQ demodulated signal

From demodulated signals from different corrosion samples, the amplitude and phase features can identify corrosion progression, as shown in Figures 5(f)(g). However, the amplitude and phase features for different corrosion stages overlaps each other which makes it difficult to distinguish the corrosion stages. Skewness feature of transient response is developed for robustness improvement.

3.3 Skewness Feature of Transient Response Results

The skewness feature is calculated using *skewness()* function in Matlab and is analysed for corrosion characterisation, as shown in Figure 6(b). Resonant frequency shift feature results are also investigated for comparison. Both features have linear relationship with corrosion progression except a change from M6 to M10. Comparing with the resonant frequency feature from RSSI shown in Figure 6(a) as well as amplitude and phase features in Figures 5(f)(g), the skewness feature has higher sensitivity and lower error bar.



(a) (b)

Figure 6. (a) Resonant frequency feature and (b) Skewness feature of IQ transient response for corrosion progression

To validate the robustness of the skewness result, the robustness testing is undertaken with different lift-up distance. The reader antenna is placed above the testing sample with distance of 10cm and 15cm in two testing. As the results illustrate in the Figure 7, the corrosion trend among the progression sample is same. The extracted skewness features of both 10cm and

15 cm test distance have increasing trend from 1 month to 6 month and decrease at 10 month and increase again at the 12 month corrosion, as shown in Figure 7. Although the values of the skewness features at 10cm and 15cm are different, the dynamic range is independent with lift-off distance.

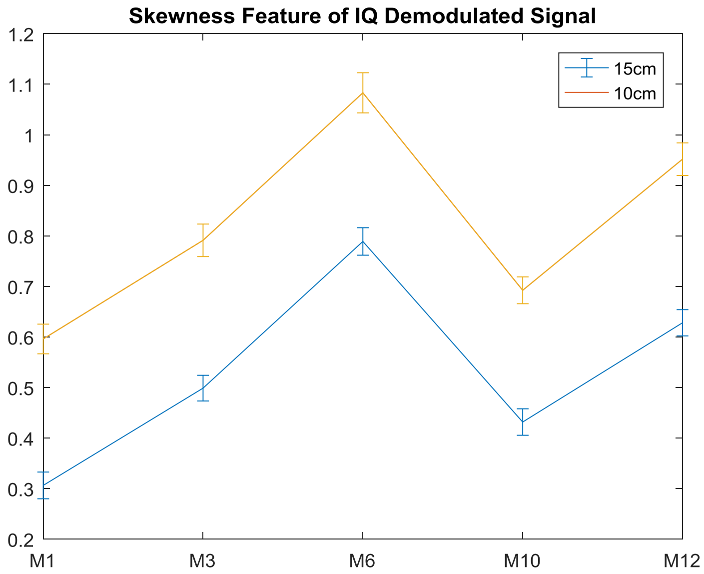
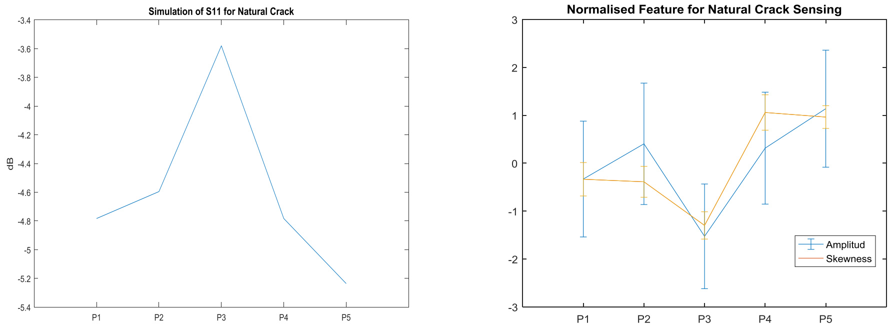


Figure 7. Skewness feature based on IQ signal at different distance

3.4. Natural Crack Evaluation using the Proposed Skewness Features

The simulation for crack sensing is set up with slot metal loss model. The width of the slot is set as 0.5mm and the length is set as 10mm to match the sample condition. The depth is set as 10mm and the simulation result show the sensor is not sensitive to the depth variation as long as the depth is larger than 1mm. From the results, the sensor has highest S11 in P3 which means it has lowest power transmitting ability at crack position. There is asymmetric result in the two side of the crack where the S11 of P1 and P2 is higher than P5 and P4. This is caused by the asymmetric structure of the sensor. When the sensor is rotated by 180^{o} in simulation, the S11 of P5 and P4 is higher than P1 and P2.

The experiment results of natural crack testing validate that the crack can be detected using both amplitude feature and skewness feature, as shown in Figure 8 for comparison of natural crack evaluation using simulation in Figure. 8(a) and experimental measurement in Figure 8(b), where the asymmetric responses around the cracks are caused by the design antenna. Both results reach minimum value at position P3 and higher value in other positions. The error bar indicates the skewness feature is more robust of material influence than the amplitude feature. The results using skewness feature shows flat trend in P1 to P2 and P4 to P5 and sharp decrease and increase in P2 to P3 and P3 to P4. This indicates the skewness feature has better sensitivity for crack sensing. The results for P1 and P2 is lower than P4 and P5.



(a) (b)

Figure 8. Natural crack sensing comparison (a) S11 of tag sensors for crack sensing with simulation, (b) comparison of normalised features for natural crack experimental measurement

4 Conclusions and Future work

Transient response of IQ signal based corrosion characterisation method for RFID sensor system has been proposed and investigated in this paper. Skewness feature of transient response from IQ signal is used for corrosion characterisation. The experimental studies have demonstrated that the proposed RFID sensor system and feature used has better sensitivities than previous RSSI or power scattering RFID sensor systems. The robustness of skewness based IQ signal transient feature is also validated through experiment. The skewness feature of IQ transient response is also applied for natural crack sensing and show improved sensitivity and robustness compared with previous IQ amplitude feature.

In the future work, high gain antenna sensor using emerging material and challenging application such as stress monitoring will be investigated. Different code modulation with truncated frequency modulation can be investigated for quantitative non-destructive evaluation (QNDE).

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