



Monitoring evolution of debris-filled damage using pre-modulated wave and guided wave ultrasonic testing (GWUT)

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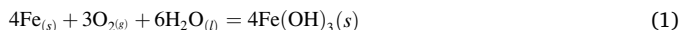
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ABSTRACT

Metals are essentially used to construct structures of high economic importance, but their service life is shortened by damage such as crack, corrosion, cavity, and dents. Damage to structure causes gradual degradation of its strength and compromises its load-carrying capacity. Some damage could be designed against but pitting corrosion, especially when it is filled with debris that would hide it and deepen its perforation activities. In this work, monitoring the evolution of debris-filled damage in structure is studied using pre-modulated wave and guided wave ultrasonic testing (GWUT). The structural responses in the varying percentage of debris-filled damage were processed using Fast Fourier Transform (FFT), Hilbert Transform (HT) and correlation techniques. The regression analysis of debris-filled damage resulted in empirical predictive models that could detect the damage and percentage of debris that might have filled it with average percentage errors of 1.34 and 0.21, respectively. The debris in the damage caused an overmodulation of the high-frequency signal. The intensity of the lower sideband (LSB) was observed to be very sensitive to variations in the damage than the upper sideband (USB). The transmission power efficiency of modulation sidebands increased proportionally with debris-filled damage percentage and could serve as a damage index.

1. Introduction

Damage in a metallic structure entails gradual degradation of structure performance due to the initiation and growth of defects that alter the structure's properties [1]. Fundamentally, defects start from the micro stage and graduate into a macro stage that could cause catastrophic failure of the structure if unrestrained. Some possible damage commonly found in structures are cracks, dents, and corrosion of different forms [2]. Corrosion is an enemy of metallic structures that degrades their strength and elasticity and shortens their useful service life [3–6]. Corrosion can form in the existence of other forms of structural damage. Primarily, corrosion happens in the presence of three core components: metal(solid), Oxygen ($O_{2(g)}$) and water ($H_2O_{(l)}$). Eq. (1) is an oxidation reaction of metallic iron with water in the presence of air [3].



Corrosion occurs in different ways in metallic structures with a singular target of limiting their lifetime of service. Oxygen and water are readily available in the environment where costly metallic structures are

deployed. Pitting corrosion is one of the corrosion types that has been seen to be more grievous than others when it existed [7–9]. It is one of the most localised forms of corrosion that occurs in an aggressive environment, as could be seen in the oil and gas industry [5], marine industry [10] and in an environment that is rich with halides [7,11]. Its formation is mostly restricted to a small surface area of the host structure to cause stress raiser [12]. The formation of stress riser in structures would result in fast catastrophic failure if not detected early. Also, the activities of pitting corrosion could lead to structural failure via progressive perforation, resulting in stress corrosion cracking. It is particularly difficult to design against pitting corrosion, unlike other forms of corrosion. A small, narrow pit with minimal metal loss can lead to structural failure. In practice, when damage (cavity, dent, notch or crack) is formed in a metallic structure, it could be covered by trapped debris and substances that speed up corrosion activities and advance the pitting of the structure. The damage could be open or covered with a semi-permeable membrane of corrosion products or other trapped debris. The covered damage could accelerate the activities of severe pitting corrosion and initiate the weakest point for stress concentration that could lead to structural failure. Localised damage in the protective

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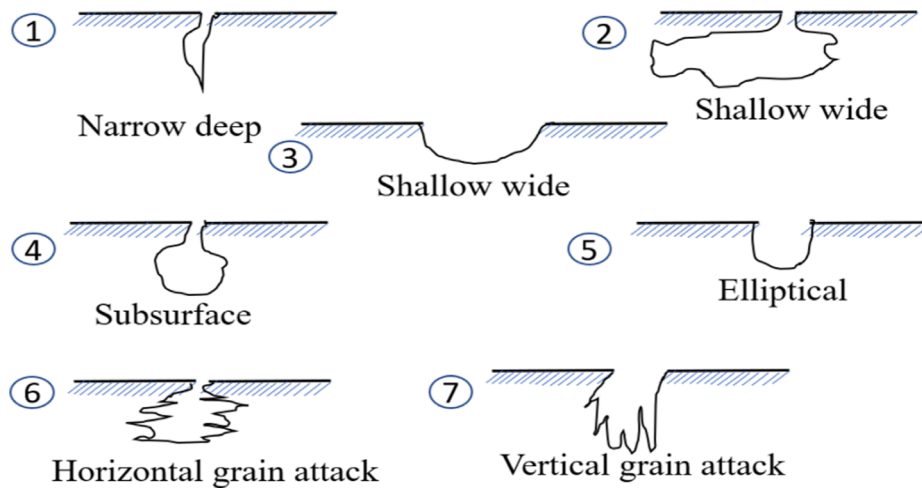


Fig. 1. Morphology of common shapes of pitting corrosion [10].

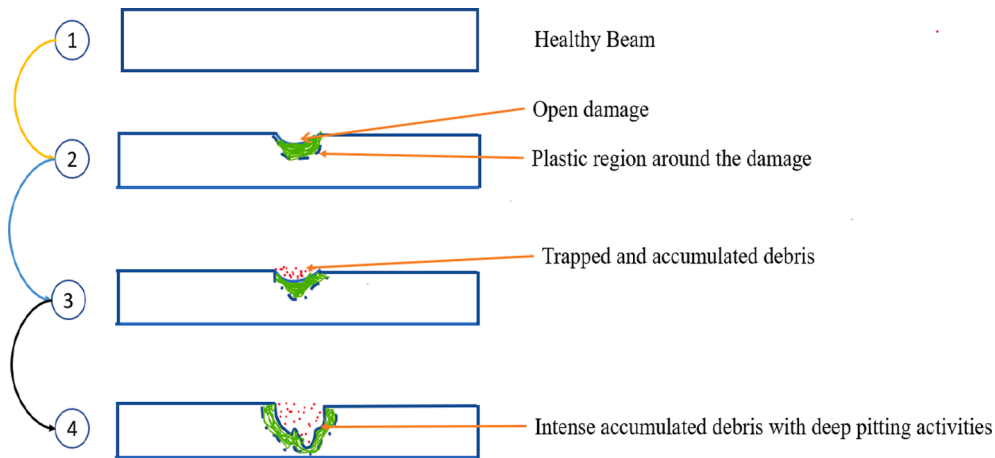


Fig. 2. The deterioration stages in pitting corrosion.

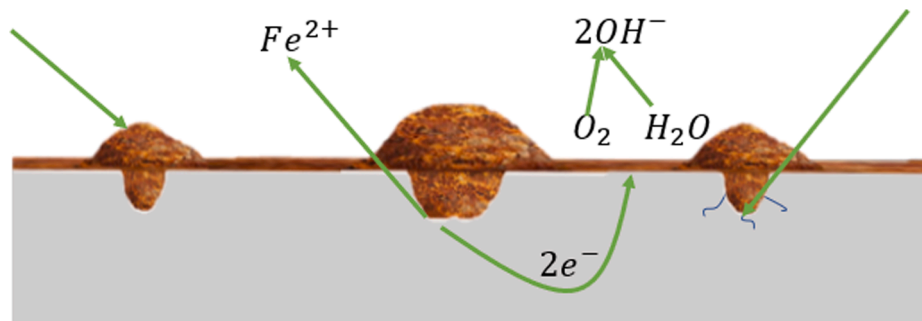


Fig. 3. The mechanism of corrosion.

layer due to chemical or mechanical sources or poor application can initiate pitting corrosion [10]. Fig. 1 shows the morphological shapes of pitting corrosion that typically forms in structures:

Most of the studied surface structural damage were dry and empty types [13–16]. Nature does not allow a vacuum; hence, any formed surface structural damage in the field of operation would be filled with debris over time. The debris could be mixed particles trapped and stuck in the damage. The continual accumulation of the debris would close the damage and promote the activities of pitting corrosion [16]. The covered damage creates an illusion of structure continuity but jeopardises its integrity in real life. The stages in pitting corrosion are provided

in Fig. 2. These stages led to a damage closure as described below. **Stage 1** depicts a healthy structure without damage, especially cavity, notch, crack and deep scratch. **Stage 2** represents the scenario when damage is created in the structure without particle accumulation. At this point, the structural loading capacity has been jeopardised. Deterioration of the structure's elasticity property gradually starts as the damaged area transits into the plasticity region. **Stage 3** depicts the environmentally aided particle deposition entrapped in the damaged spot. The trapped heterogeneous particles in a moist atmosphere would lead to observable rust films. The formed corrosion product would gradually be gelled with time as the particles gain good adhesion to the damaged surfaces, hiding

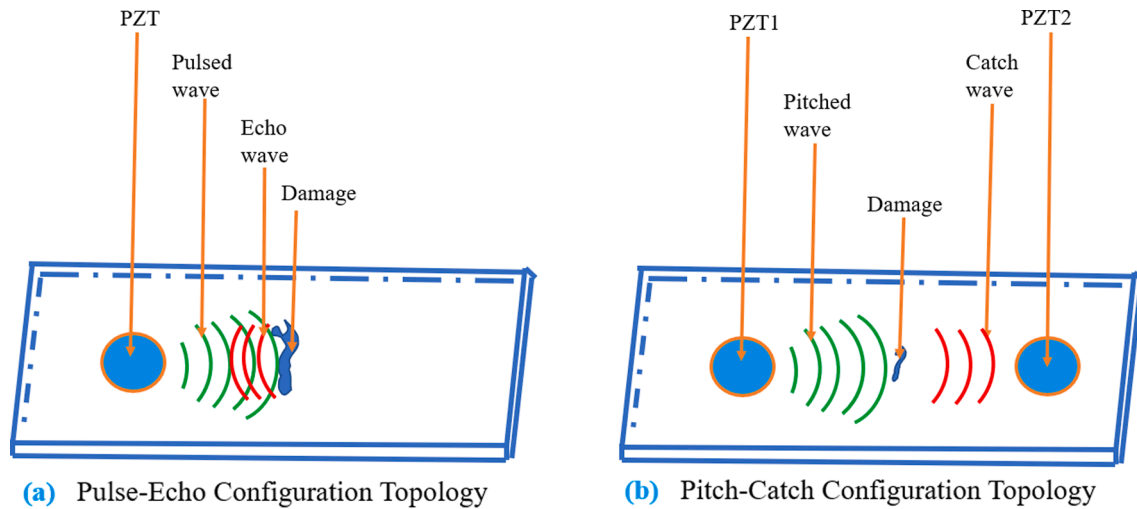


Fig. 4. Active mode transducers configuration topology.

the damage and creating a fake continuity of the structure, as shown in Fig. 3. The accumulated debris and corrosion-prone particles could be less prevalent in a dry atmosphere than in a humid atmosphere and provide a mechanism for increased crack closure and deepening of the material perforation that would usher in **stage 4**. Pitting corrosion is difficult to detect, especially when covered by debris. Some grievous pitting corrosion has a small pit at the structure's surface but a large size beneath [5]. Hence, to avoid grievous pitting corrosion from forming and advancing through debris-filled damage, there is a need for early detection of debris-filled damage. Most studies focused on detecting and evaluating empty dry damage (such as crack, delamination, debonding, and dent) in isotropic or composite structures using guided waves [8,17,18]. This work proposes and implements a novel debris-filled damage detection using long-length pre-modulated excitation wave and a new damage index.

This paper provides, in section-2, the relevant theory about the wave-damage interaction, modulation of interacted signals for damage prediction and the methods to process these signals. The theoretical description of section-2 establishes the base for selecting the methods and materials as described in section-3. Section-3 also contains the complete details of an experimental scheme to collect the data for novel debris-filled damage detection with the long-length pre-modulated excitation wave. In section-4, the experimental results are presented and discussed. The conclusions are provided at the end of section-5.

2. Theory

2.1. Wave-Damage interaction and effects

Ultrasonic waves have been extensively used to detect and evaluate damage existence in structures by analysing wave-structure response signals. The waves could be generated through passive or active mode [2,19]. Passive mode occurs when the received response signals are due to the crack propagation mechanism. The sound wave generated in passive mode is often referred to as acoustics emission (A.E.) [20], which happens only during active crack propagation. In an active mode, the propagating wave is generated through excitation of the actuator or striking the structure with an excitation hammer [21]. The configuration topology of the transducer often used in active mode is Pitch-Catch or Pulse-Echo [2,22,23], as in Fig. 4. In Pulse-Echo configuration topology, one or more transducers are used. Using only a transducer in pulse-echo configuration, it would be programmed to actuate an interrogative wave at one time and sense the reflected response wave at another time. This configuration is suitable when inspecting for structural damage that can cause a reflection or an echo of good intensity. In Pitch-Catch

configuration topology, at least two transducers are used. One of the transducers functions as an actuator, and the other functions as a sensor [23].

Various Nondestructive testing (NDT) techniques exist to inspect and evaluate damage presence and structural integrity [24]. These techniques are visual, thermographic, eddy current, radiographic, and guided wave ultrasonic testing (GWUT) [25]. GWUT is advantageous for long-range and full coverage inspection of structures without significant structural modification [2,26–29], which minimises inspection drudgery and enhances daily work output [2,30], unlike other NDT techniques. GWUT could be used for linear and nonlinear damage-related feature detection [31–33]. The linear testing method has been majorly used to detect defects of reasonable sizes. It could be unsuitable for early-stage or corrosion damage activity detection, such as debris-filled damage.

In about 1960s, Zarembo and Krasilnikov conceptualised a method of structural integrity inspection called Nonlinear Wave Modulation Spectroscopy (NWMS) [34–36]. It was used in building structures around the 1990 s and has been further researched and used in many instances for structural health monitoring (SHM) [36]. The NWMS uses a single high-frequency wave introduced into the structure through the piezoelectric transducer (PZT) [37]. This high-frequency wave is the carrier wave that a low-frequency signal modulates. Impact hammer [38] and material testing system (MTS) [36] have been predominately used to inject a low-frequency signal into the structure, while PZT is used to inject a high-frequency signal. There is often inconsistency in the use of impact hammer and high cost in acquiring MTS for injection of low-frequency signal in the structure. These have limited the adoption of the nonlinear damage detection method in practice. Interpretation of the nonlinearity effect in the response signal and accurately relating them to damage when more than one phenomenon could cause such is challenging [37,38]. Although in [39], the authors developed a theoretical framework for mixing frequency techniques and used it in [28] to detect impact damage by counting spectral peaks. It is still challenging to credit all the formed spectral peaks to damage existence in the structure. We used a pre-modulated excitation signal to enhance the ease of interpreting the response signal and consistency in signal modulation. This signal is created in the methods and materials section, while its theoretical formulation is discussed in section 3. Unlike the Nonlinear modulation, only two distinct sidebands and the carrier band signals would be formed using the pre-modulated wave. The interaction of the propagating wave with the defined damage would be manifested in the variation of the sideband's magnitude, as noted in the result analysis section. We used the internal low-frequency of the arbitrary function generator to modulate the high-frequency carrier wave. This approach

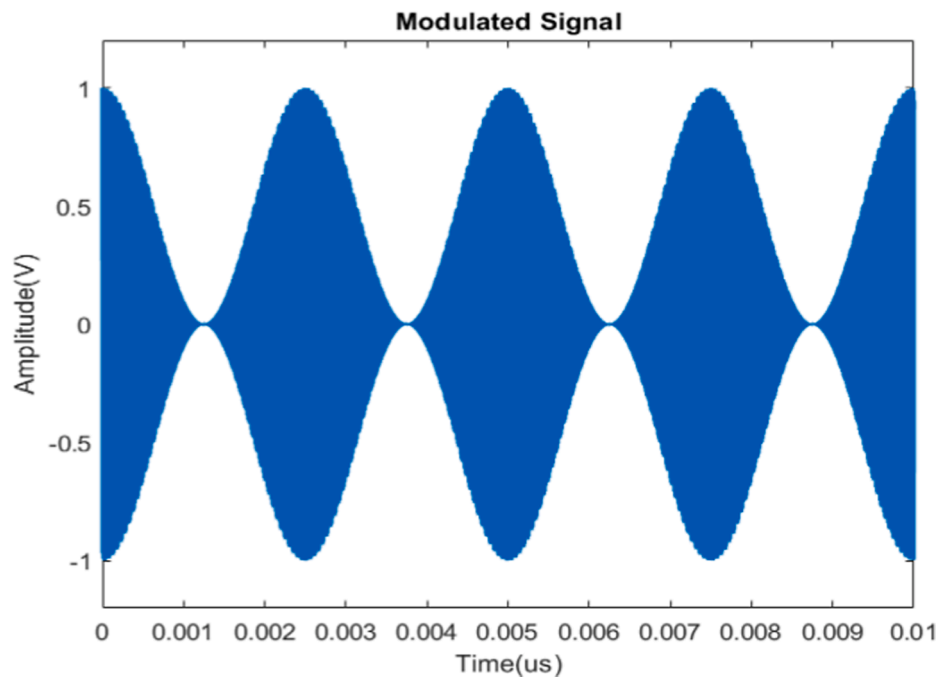


Fig. 5. The generated modulated excitation signal.

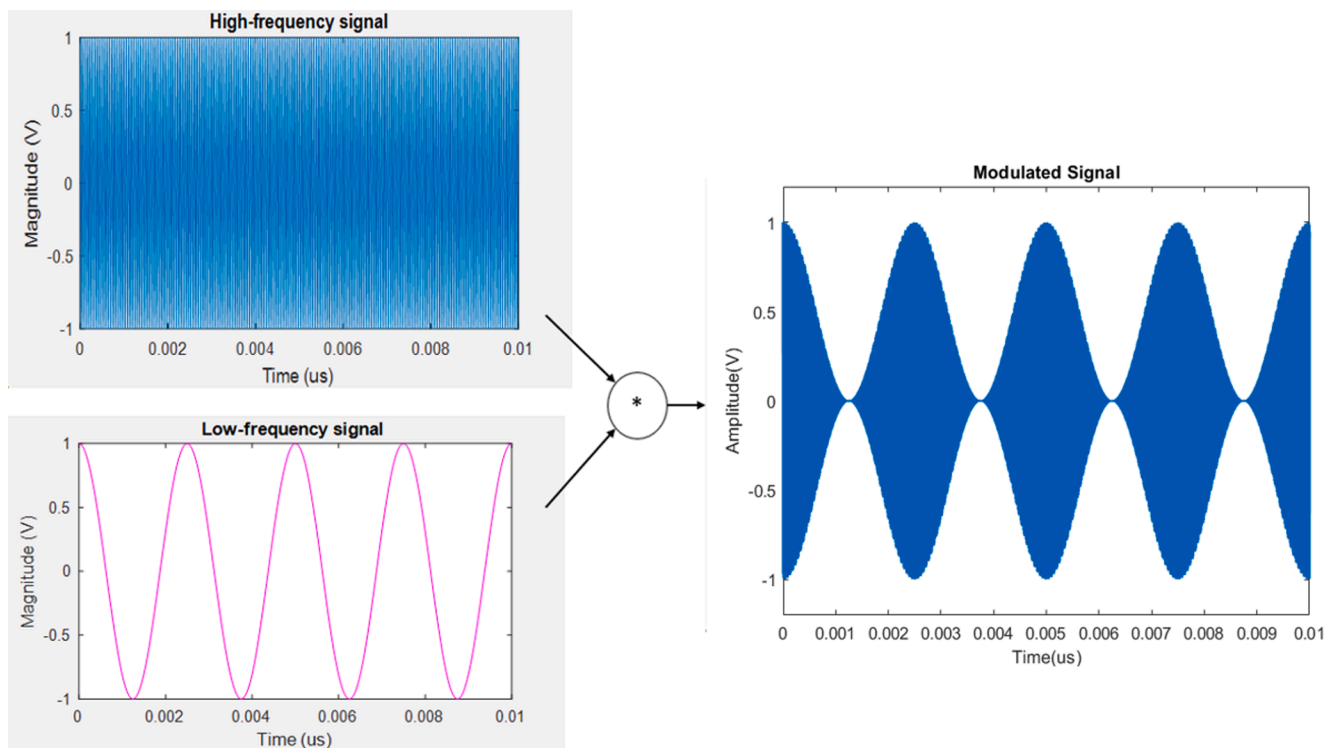


Fig. 6. Amplitude Modulation of the excitation signal.

generated modulated packet waves, typically as in Fig. 5.

2.2. Amplitude modulation theoretical formulations and analysis

Modulation is the act of varying any key three parameters (Amplitude, Frequency and Phase) of the carrier wave signal with a low-frequency wave signal that could be referred to as the message signal [35]. If a signal of low value varies the carrier wave's amplitude,

frequency, or phase, the process is called amplitude modulation, frequency modulation, or phase modulation, respectively [35]. This study adopted wave amplitude modulation to generate a continuous wave packet that would squeeze and relax the PZT actuator and cause the structural atoms to vibrate about their mean positions. Unlike Nonlinear Wave Modulation Spectroscopy in [34–36], the interrogating packet waves would be generated before being introduced into the structure through the PZT actuator. Through this approach, the modulation index

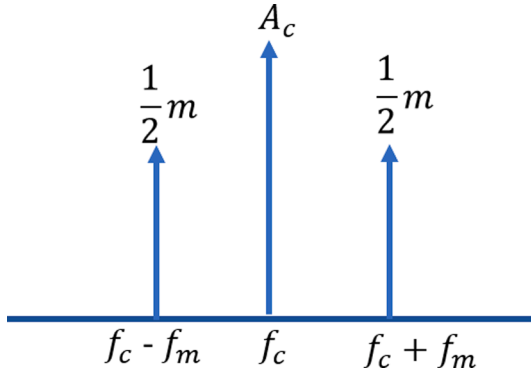


Fig. 7. Typical frequency domain spectrum of AM signal.

of wave signal before injection into the structure with and without damage could be easily estimated, and variations accompanied after that would be an attribute of the damage existence in the structure. The formation of excessive sidebands would be minimised as damage detection would be based on the variation of the upper sideband and lower sideband strength relative to the carrier signal component. Fig. 6 depicts a typical wave amplitude modulation. It could be seen that the low-frequency signal determines the number and duration of the amplitude modulated packet waves.

Let's assume the high-frequency wave signal shown in Fig. 6 is represented in Eq. (2) as the carrier wave signal. And the needed low-frequency signal to modulate the amplitude of the high-frequency wave signal is as in Eq. (3b).

$$y_c(t) = \cos(\omega_c t) \quad (2)$$

$$y_m(t) = m \cos(\omega_m t) \quad (3a)$$

where

ω_c = high angular frequency of the carrier signal component.
 ω_m = low angular frequency of the message signal component.
 m = intensity of the message signal component.

To achieve modulated wave packets that would excite the transducer actuator, an offset amplitude, A is introduced to the low-frequency signal to form the modulating signal given in Eq. (3b).

$$\hat{y}_m(t) = A + m \cos(\omega_m t) \quad (3b)$$

Using Eq. (3b) to modulate Eq. (2) results in Eq. (4c) which is called the modulated wave signal. Assuming the structure is a lossless type devoid of attenuation effect, the received response signal by the sensor transducer would be akin to the generated signal. This is analogous to message transmission in radio communication.

$$y(t) = \hat{y}_m(t) * y_c(t) \quad (4a)$$

$$y(t) = (A + m \cos(\omega_m t)) * \cos(\omega_c t) \quad (4b)$$

$$y(t) = A \cos(\omega_c t) + m \cos(\omega_m t) * \cos(\omega_c t) \quad (4c)$$

Taking normalisation of Eq. (4c) resulted in Eq. (4b).

$$y(t) = \cos(\omega_c t) + \frac{m}{A} \cos(\omega_m t) * \cos(\omega_c t) \quad (4d)$$

Applying trigonometry identity to Eq. (4d) to obtain Eq. (5).

$$y(t) = \cos(\omega_c t) + \frac{1}{2} \frac{m}{A} [\cos((\omega_c - \omega_m)t) + \cos((\omega_c + \omega_m)t)] \quad (5a)$$

$$y(t) = \underbrace{\cos(\omega_c t)}_1 + \underbrace{\frac{1}{2} \frac{m}{A} \cos((\omega_c - \omega_m)t)}_2 + \underbrace{\frac{1}{2} \frac{m}{A} \cos((\omega_c + \omega_m)t)}_3 \quad (5b)$$

where $\omega_c = 2\pi f_c$; f_c = carrier or high frequency; $\omega_m = 2\pi f_m$; f_m = message or low frequency or modulating frequency.

From Eq. (5), it is theoretically evident that the power spectrum of amplitude modulated signal possesses three components signals before being injected into the structure for interaction or integrity query. These components are the carrier or centre frequency and the two sidebands surrounding the carrier component. Expressing this in a typical power spectrum graph would be as in Fig. 7. In a situation of no amplitude modulation, there won't be the formation of sidebands.

The extent or depth of the carrier wave modulation in the time-domain could be estimated using Eq. (5).

$$\text{Modulation index } M_i = \frac{\tilde{d}}{d} \quad (5a)$$

where

$$\tilde{d} = V_{max} - V_{min} \quad (5b)$$

$$d = V_{max} + V_{min} \quad (5c)$$

V_{max} = the maximum peak of the time-domain signal response.

V_{min} = the minimum peak of the time-domain signal response.

While in the frequency domain, the modulation index could also be estimated using Eq. (5d).

$$\text{Modulation index } M_i = \frac{m}{A_c} \quad (5d)$$

$$m = A(f_c - f_m) + A(f_c + f_m) \quad (5e)$$

m = the sum of the two sidebands amplitudes.

A = amplitude of the carrier signal.

The modulation index signifies the extent to which the low-frequency signal modulated the amplitude of the high-frequency signal. The modulation index could be 1, implying that the carrier signal amplitude is perfectly modulated. This is quite difficult to realise in most experimental cases as the modulation extent could be affected by wave-structure interaction and wave-damage interaction. The most achieved modulation indices are under-modulation when the modulation index is < 1 and over-modulation when the modulation index is > 1 . If under-modulation occurs, it signifies that the amplitude of the carrier signal is greater or much greater than the message signal amplitude. In the case of under-modulation, the modulation index is below 1 ($N < 1$), while over-modulation is greater than 1 ($N > 1$). The modulation index categories are expressed in piecewise definition below.

$$N \begin{cases} = 1; \text{perfect modulation} \\ < 1; \text{Under-modulation} \\ > 1; \text{Over-modulation} \end{cases} \quad (6)$$

2.3. Structural response signal processing techniques

After interaction of the propagating querying waves with the structure and debris-filled damage, the response signal would be collated and further processed. We employed Fast Fourier Transform (FFT) to ascertain the response signal's frequencies and intensity components. Hilbert Transformation (HT) was used to extract the envelope signal and compute its FFT, while the correlation technique was used to estimate the similarity between the reference signal and various response signals.

2.3.1. Fast Fourier Transform (FFT) of t-domain signal

FFT is used extensively in signal processing to transform signals from a time domain into a frequency domain for easy analysis [40]. As the sensor signal is recorded in the time domain, it is tedious to ascertain the different superimposed components that formed it. Hence, the need for frequency-domain transformation. A Fast Fourier Transform (FFT) is a special algorithm that is prominently used to compute the frequency components, $X(\omega)$ of a continuous time-domain signal, $x(t)$. This is

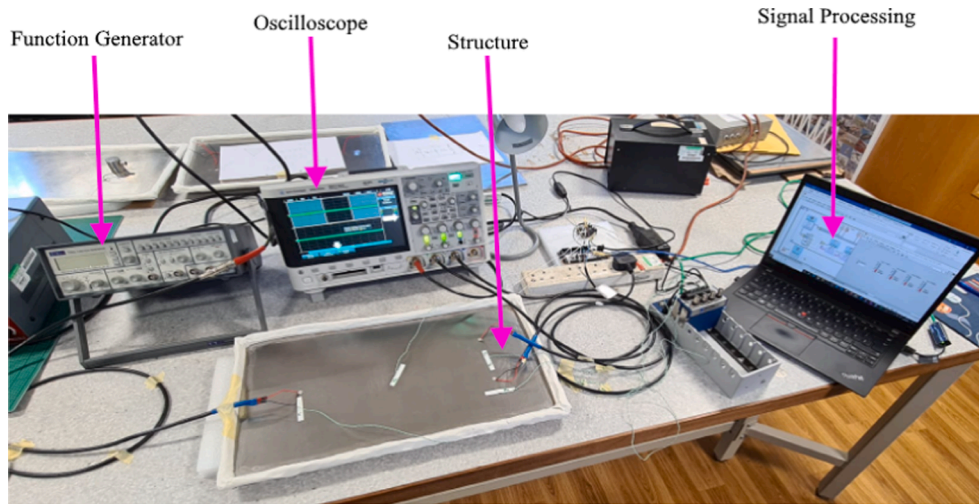


Fig. 8. The Experimental testing rig.

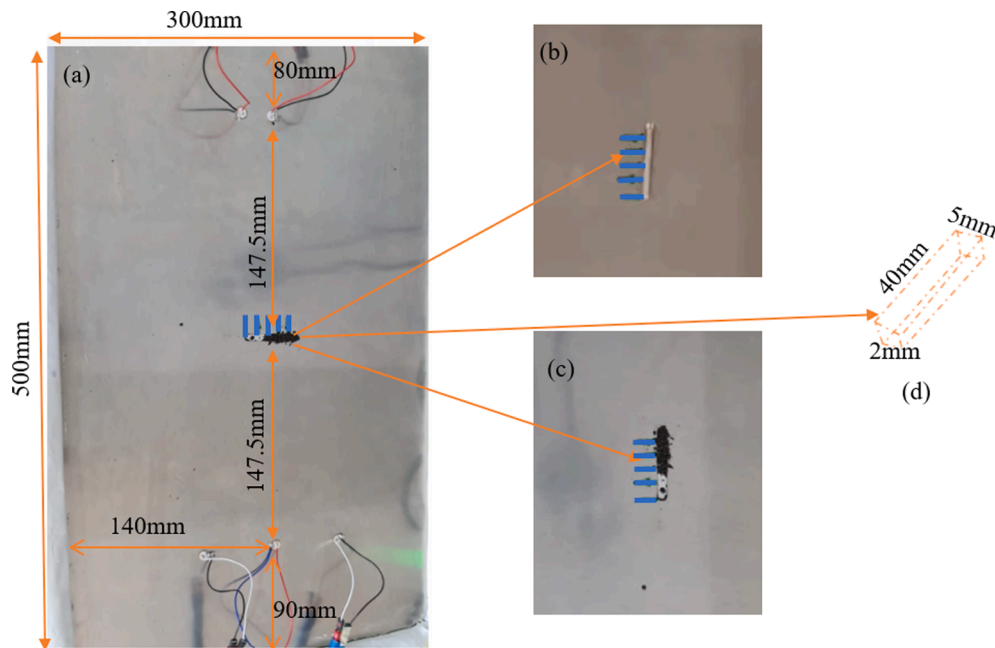


Fig. 9. (a) The complete structure with sensor and damage (b) the empty machined damage debris-unfilled (c) Debris-filled damage (d) dimension of the damage. NB: The marked blue lines indicate the debris filling percentage.

Table 1

Mechanical properties of mild Carbon Steel.

Material	Young modulus, E (N/m ²)	Poisson's ratio, ν	Density, ρ (kg/m ³)	Length, L(mm)	Width, W(mm)	Thickness, T _h (mm)
Carbon steel	2×10^{11}	0.289	7800	500	300	3

Table 2

Percentage corrosion debris coverage of the crack.

S/N	Crack Percentage of fill	Debris-filled length	Debris-unfilled length	Crack depth
1	Empty	0.00 mm	40.0 mm	2.00 mm
2	20%	8.00 mm	32.00 mm	2.00 mm
3	40%	16.00 mm	24.00 mm	2.00 mm
4	60%	24.00 mm	16.00 mm	2.00 mm
5	80%	32.00 mm	8.00 mm	2.00 mm
6	100%	40.00 mm	0.00 mm	2.00 mm

explicitly expressed in Eq. (7). FFT is widely used in NDT to analyse response signals recorded from sensor transducers to determine the signal's constituted components.

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)e^{-j\omega t} dt \quad (7)$$

2.3.2. Correlation of signals

The correlation technique is often used in the signal processing of patterns to determine the similarity of one signal relative to the other

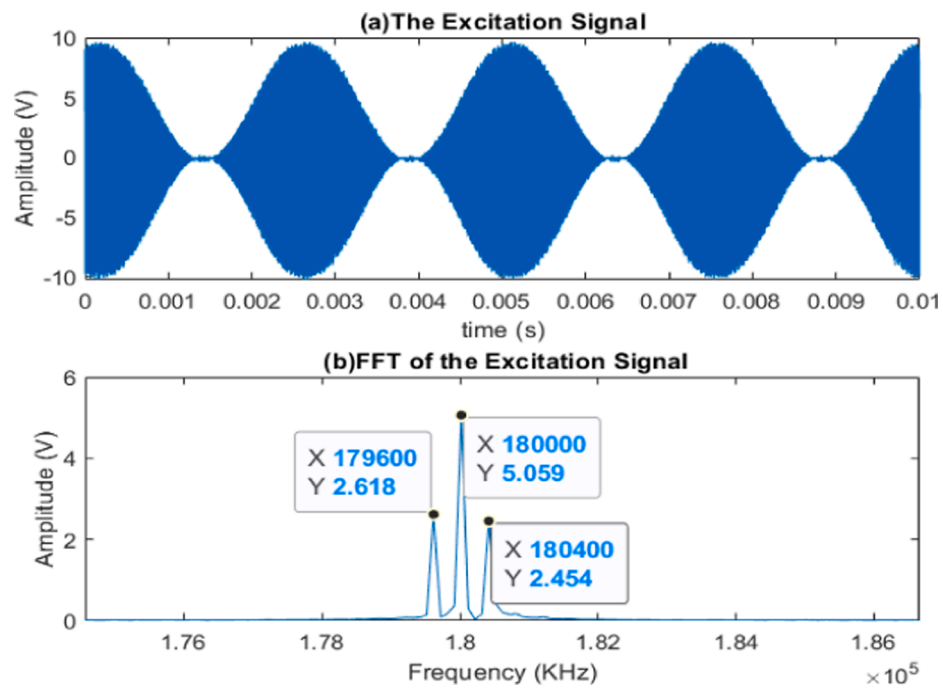


Fig. 10. (a) The recorded excitation signal (b) The FFT of the recorded excitation signal.

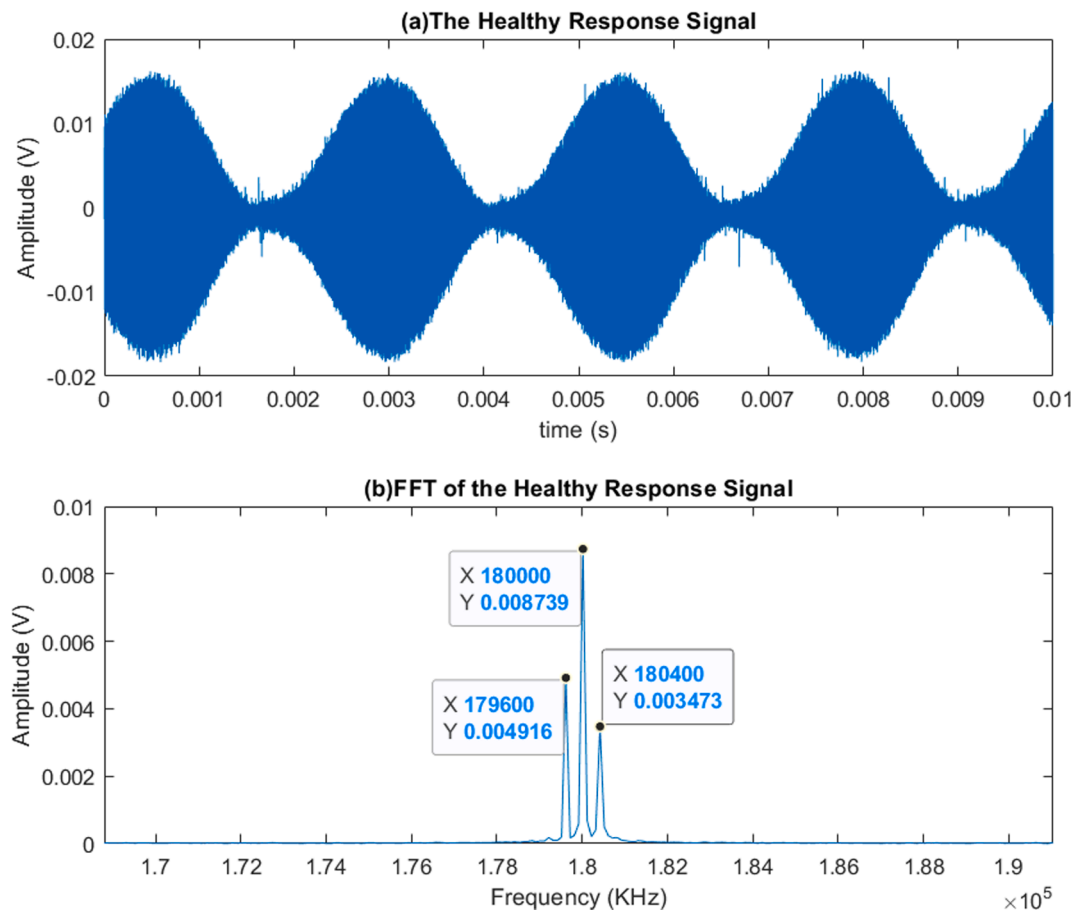


Fig. 11. (a) The healthy response signal (b) The FFT of the healthy response signal.

signals of interest [41]. If two comparing signals match, their maximum matching peak will occur at the zero-origin. This often happens when a signal matches itself, called autocorrelation, while cross-correlation

involves matching two different signals. From a statistical point of view, if the correlation coefficient score of the comparing signals is zero, they are said to be uncorrelated, as in Eq. (8). The nonlinearity effect of

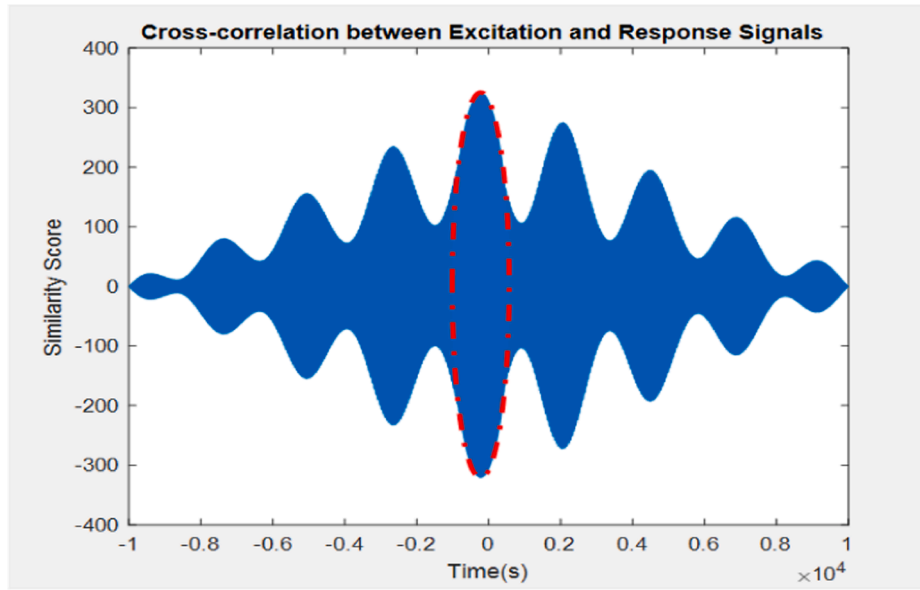


Fig. 12. The Cross-correlation between the excitation signal and the response signal of healthy structure.

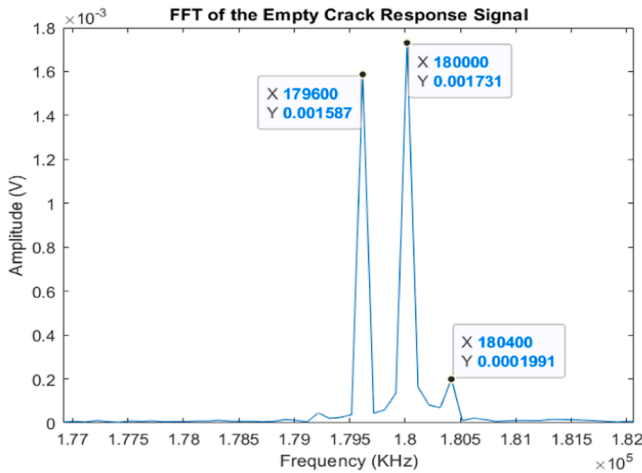


Fig. 13. The FFT of the response signal when empty damage is initiated in the plate.

damage in ultrasonic signal response could be detected by determining the correlation between the reference signal and response signal before and after damage initiation in the structure. The presence of lag or lead time could signify the existence of a defect in the structure. Eq. (9) could be used to compute the time delay or lead to a mismatched comparison [42]. It is worthy to note that cross-correlation is less sensitive to background variations or noise interference in signals as it may not affect all of the component peaks and would be attenuated.

$$\text{Uncorrelated, } \rho(x, z) = 0 \quad (8a)$$

$$\text{Correlated, } \rho(x, z) \neq 0 \quad (8b)$$

$$\rho(x, y) = \frac{\text{Cov}[x, y]}{\sqrt{\text{Var}[x]\text{Var}[y]}} \quad (8c)$$

x and z are two comparing signals. Cov denotes the covariance of x and z while Var denotes variance.

$$R(\tau) = \int_{-\infty}^{+\infty} x(t)y(t - \tau)dt \quad (9)$$

Where.

x and y are functions of time.

τ is the time delay, and it could be negative, zero or positive. R is the cross-correlation with time delay τ .

2.3.3. Hilbert transformation (HT)

The first prime in Nondestructive testing is to detect damage before further analysis of the characteristics of the damage. In radio communication, it is opined that integrity signals are contained in the message signal, which is the modulating signal. Since the response signal is a composite of signals, there is a need for separation and extraction, especially the envelop signal. Hilbert Transformation (HT) is useful in extracting the modulating low-frequency signals that envelop the carrier signal [43–19]. The HT technique transforms the modulated real response signal into an analytical signal that could be expressed in the complex plane and then makes the computation of instantaneous amplitude and instantaneous phase easier. If the response signal captured by the sensor is, $x(t)$, its transformation into an analytical signal could be computed using Eq. (10b).

$$Z(t) = Z_r(t) + jZ_i(t) \quad (10a)$$

$$Z(t) = x(t) + jHT[x(t)] = A(t)e^{j\phi(t)} \quad (10b)$$

Where $jHT[x(t)]$ is the real signal but transformed into a complex plane.

The modulation envelope or instantaneous amplitude is computed using Eq. (11a).

$$A(t) = \sqrt{Z_r^2(t) + Z_i^2(t)} \quad (11a)$$

Also, the instantaneous phase of the modulated signal is computed using Eq. (11b).

$$\phi(t) = \tan^{-1} \left(\frac{Z_i(t)}{Z_r(t)} \right) \quad (11b)$$

It is worthy of note that HT is useful for extracting the modulating signal and instantaneous frequency narrowband signals.

3. Methods and materials

The system testing rig was first conceptualised and implemented as in Fig. 8. Mild Carbon Steel is essentially used to construct civil

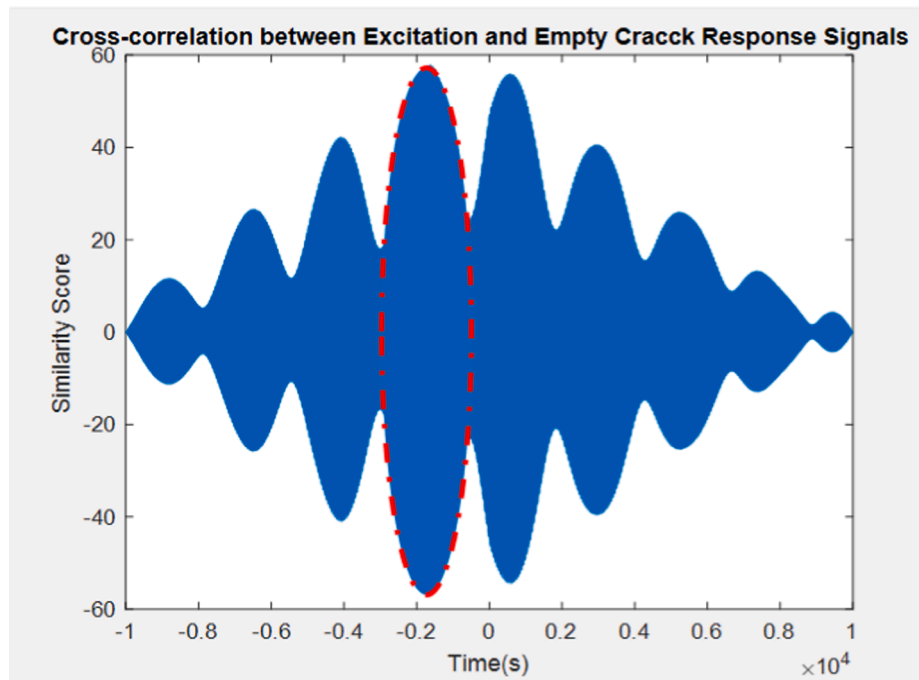


Fig. 14. The Cross-correlation between the excitation signal and the empty damage response signal.

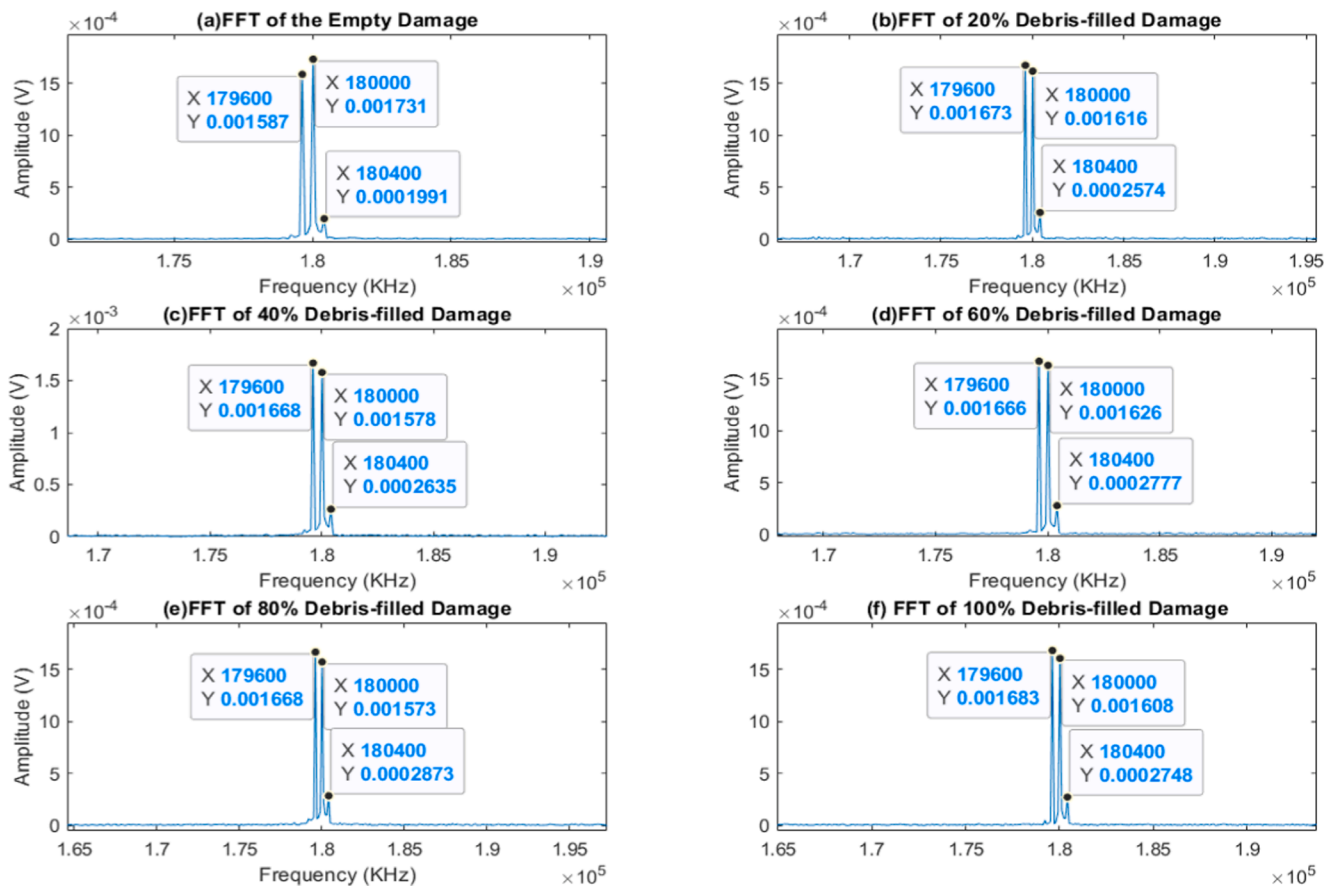


Fig. 15. The FFT of (a) Empty damage (b) 20% debris-filled damage (c) 40% debris-filled damage (d) 60% debris-filled damage (e) 80% debris-filled damage (f) 100% debris-filled damage.

Table 3
Intensities of response signal for debris-filled damage.

Response name	LSB(179600 Hz)	CB (180KHz)	USB(180400 Hz)	Modulation Index (MI)
Empty Damage	0.001587	0.001731	0.0001991	1.031831311
20% covered	0.001673	0.001616	0.0002574	1.194554455
40% covered	0.001668	0.001578	0.0002635	1.224017744
60% covered	0.001666	0.001626	0.0002777	1.195387454
80% covered	0.001668	0.001573	0.0002873	1.243038779
100% covered	0.001683	0.001608	0.0002748	1.217537313

structures, especially oil and gas pipelines. The high use of mild carbon steel is due to its low carbon content and good plastic toughness [5]. In this experimental study, we used a mild carbon plate of dimension: $500\text{mm} \times 300\text{mm} \times 3\text{mm}$. A damage of 40 mm length, 5 mm width and 2 mm depth as shown in Fig. 9 was carefully machined at the mid-distance between the transducers to simulate initial damage that would advance into pitting corrosion activities. The mechanical property of the plate is tabulated in Table 1. The edges of the plate were covered with DAS modelling Air dry clay [44] to achieve a Non-Reflective Boundary structure (NRB). The NRB helped minimise the response signal's complexity by ensuring that signals from the edges of the plate were absorbed and never reflected. The plate is separated from the experimental table surface using a soft foam to avoid vibration transfer from the table. Two ceramic transducers (PZT: $7.000\text{mm} \times 0.195\text{mm}$) were bonded on the plate using epoxy adhesive [45]. The PZTs are 102mm from the end-edges and 100mm from the side-edges while they are 300mm separated. The transducers have a resonant frequency of 285KHz and curie temperature of 340°C. One transducer served as an actuator (PZ1), and the other served as a sensor (PZ2). The PZ1 is excited with an amplitude modulated wave signal as derived in Eq. (4). The excitation signal of continuous packet triggering was generated by using the 400

Hz internal low-frequency signal of the function generator (TG550 Function Generator) to modulate the carrier frequency of 180KHz. This is called a pre-modulated excitation signal, which differs from the case of using MTS to generate the low-frequency signal or relying on the damage to generate the low-frequency to modulate the high-frequency signal injected into the structure [46]. The generated excitation signal was visualised and recorded using Agilent Technologies Mixed Signal Oscilloscope (MSO-X 3024A) with a sampling frequency of 1 MHz. 10,000 samples were recorded and processed using FFT to transform the signal from time-domain to frequency-domain and compute its frequency component's magnitude. The instantaneous magnitude of the response signal was determined using HT. A similarity match was calculated between the reference signal and response signals using cross-correlation. The following scenarios were studied:

- Interaction of the modulated wave signal with the structure when devoid of damage (Healthy state).
- Interaction of the modulated wave signal with the structure when the damage of 40mm length, 5mmwidth and 2mm depth is machined on it. Fig. 7 shows the created damage condition on the plate (Unhealthy State).
- Interaction of the modulated wave with the structure when different percentages of debris filled the damage as it would be in the early start of pit-filled corrosion damage (Debris-filled pitting scenario). Table 2 shows the percentage of debris-filled damage and the percentage of damage not filled with debris. This percentage is calculated based on the length of the machined damage.

4. Results and discussion

(A). Fig. 10 show the recorded excitation signal and its FFT. It is evident from the result that the excitation signal is amplitude modulated as it shows the two sidebands (the Lower sidebands, LSB and the upper Sideband, USB) and the carrier frequency band. The processed signal resulted in a carrier frequency of 180KHz, the lower sideband (LSB) of 179.6KHz (i.e. carrier frequency minus the modulating frequency) and

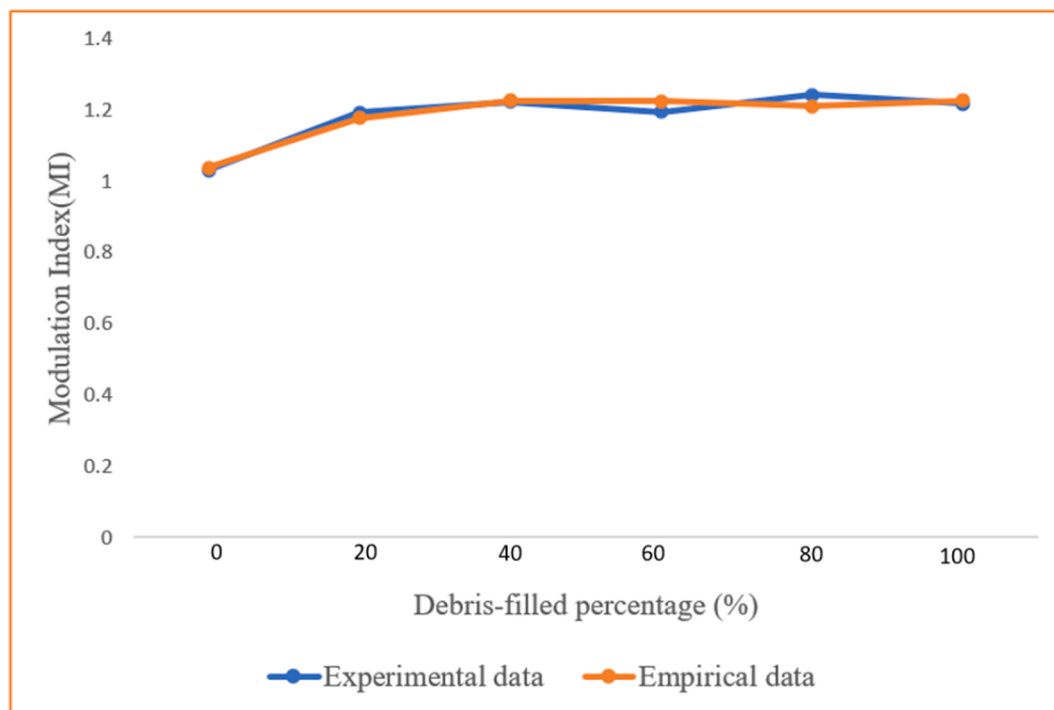


Fig. 16. The modulation index for different percentages of debris-filled damage.

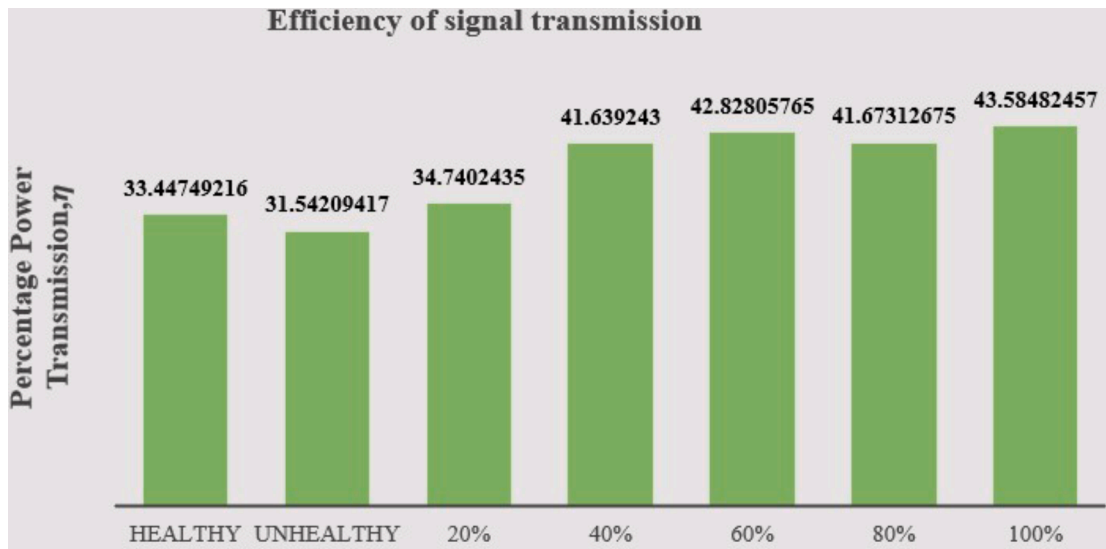


Fig. 17. The power transmission efficiency in AM (Healthy means good condition; unhealthy means empty damage; different percentages imply the amount of debris that filled the damage).

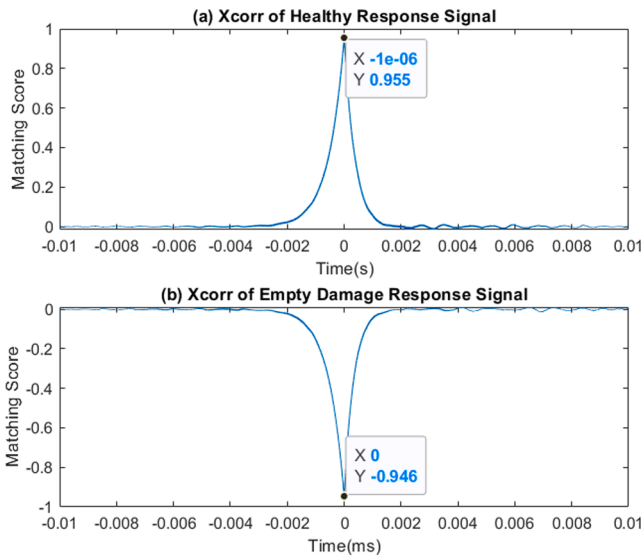


Fig. 18. (a) Cross-correlation between the reference signal and healthy response signal (b) Cross-correlation between the reference signal and empty damage response signal.

the upper sideband (USB) of 180.4KHz (i.e. carrier frequency plus the modulating frequency). From Fig. 10b, the modulation index of the excitation signal is $\frac{(2.618+2.454)}{5.059} = 1$. Since the modulation index is 1, it implied that a nearly perfectly amplitude modulated wave was injected into the structure through the actuator transducer. The response signal was received using the sensor. When the wave packets in Fig. 10a and Fig. 11a are compared, it can be seen that there is a difference in the arrival time of the wave packets. Due to the high-frequency wave used in the study and continuous injection of the excitation signal, estimating the arrival time with certainty from the time-domain response signal would not be easy. The FFT of the response signal is shown in Fig. 11b. The computed FFT result showed that the response's signal frequency of the carrier band, LSB and USB, is the same as the excitation signal. The modulation index of the response signal is 0.96, and the two sideband signals depict almost the same energy strength. This is a suggestion that there may be no damage to the structure. The cross-correlation between the excitation signal and the response signal was computed and shown

in Fig. 12. The cross-correlation showed that the two signals are nearly identical, as their highest matching peak occurred at the zero position. The little lag in the match could be attributed to the inherent inhomogeneity of the plate. The results demonstrated here affirmed that our testing rig works properly and could record integrity signals.

(B). Fig. 13 is the FFT computational result of the response signal when the defined damage was machined in the plate. We observed that the presence of the damage caused significant variation in the intensity of sideband signals. The LSB is about eight times greater than the USB. This implies that the LSB is more sensitive to damage than the USB. The upper sideband propagates with the highest frequency. Hence, it possesses the smallest wavelength. It could be that the wavelength of the upper sideband is in the range that it could be easily attenuated or suppressed by the damage, unlike the carrier frequency and the lower sideband components of the propagating wave. The debris-filled damage acts as a high-frequency cut-off filter by suppressing the upper sideband component. We then computed the damage index using the intensity of the carrier and that of the LSB. We obtained DI of 0.92, but the DI of the healthy response is 0.56. Hence, the damage could be detected using LSB and carrier intensity variation. Cross-correlation between the excitation signal and the empty crack response signal was computed to understand the effect further, as shown in Fig. 14. It is evidently from Fig. 14 that the existence of a crack in the structure caused a significant delay in the signal, which resulted in a negative uncorrelation between the excitation signal and the empty damage response signal.

(C). The FFT of the response signal when the damage is empty and when the damage is filled with dry debris was computed and shown in Fig. 15. The intensity of the LSB, USB and carrier frequencies were computed and tabulated in Table 3. The modulation index of each response signal was computed and plotted in Fig. 16. The signal modulation index was correlated with the percentage of debris that filled the damage. As the percentage of debris in the damage increases, the response signal becomes more overmodulated. This regression analysis resulted in an empirical predictive model expressed in Eq. (12). The empirical model could predict the health state of the structure, especially in debris-filled damage cases, at an error percentage of 1.34. From the computed modulation index, we observed that the propagating signal is over modulated in a situation of damage existence that is filled with debris. We deduced that the modulation indices of the debris-filled damage are at least 10% greater than the situation of empty damage. The 10% difference could serve as a debris filling inception detection threshold. Fig. 17 shows the power signal transmission efficiency. The

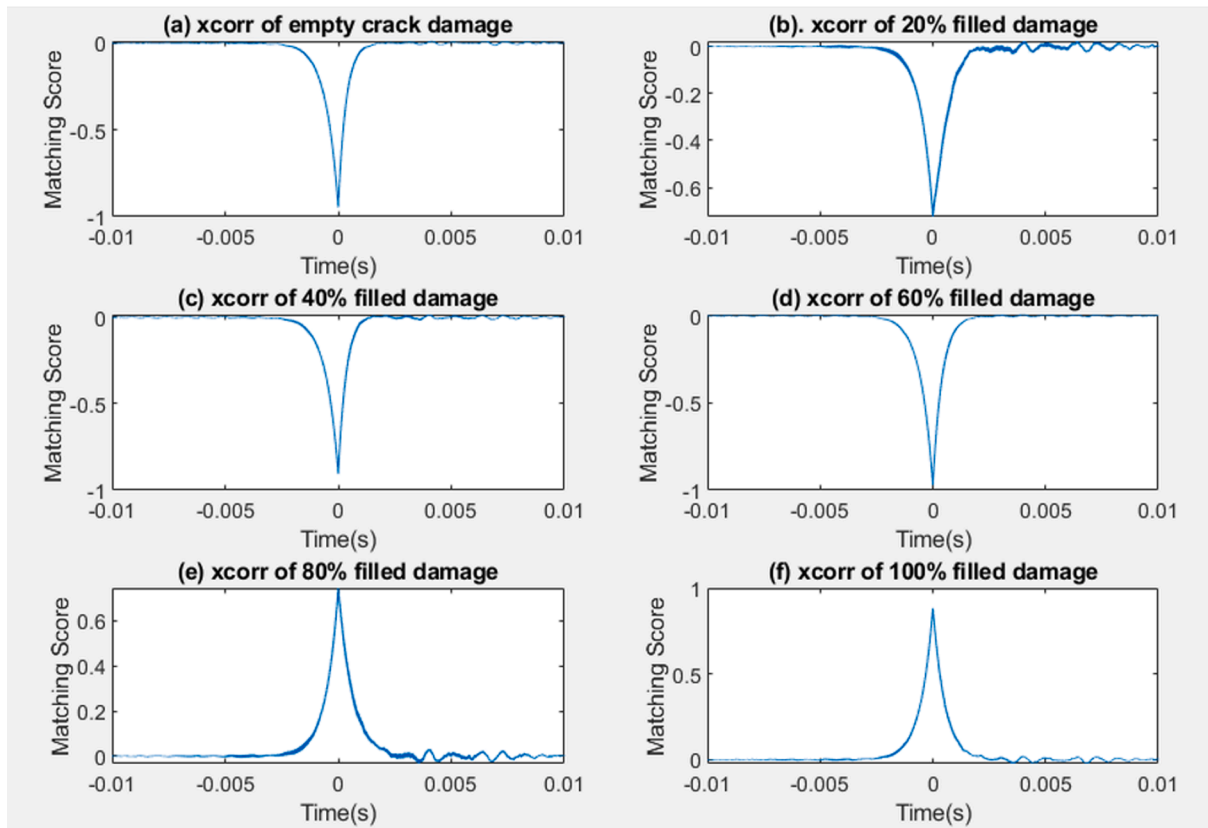


Fig. 19. The cross correlation between the reference signal and (a) empty crack damage response signal (b) 20% debris filled crack damage response signal (c) 40% debris filled crack damage response signal (d) 60% debris filled crack damage response signal (e) 80% debris filled crack damage response signal (f) 100% debris filled crack damage response signal.

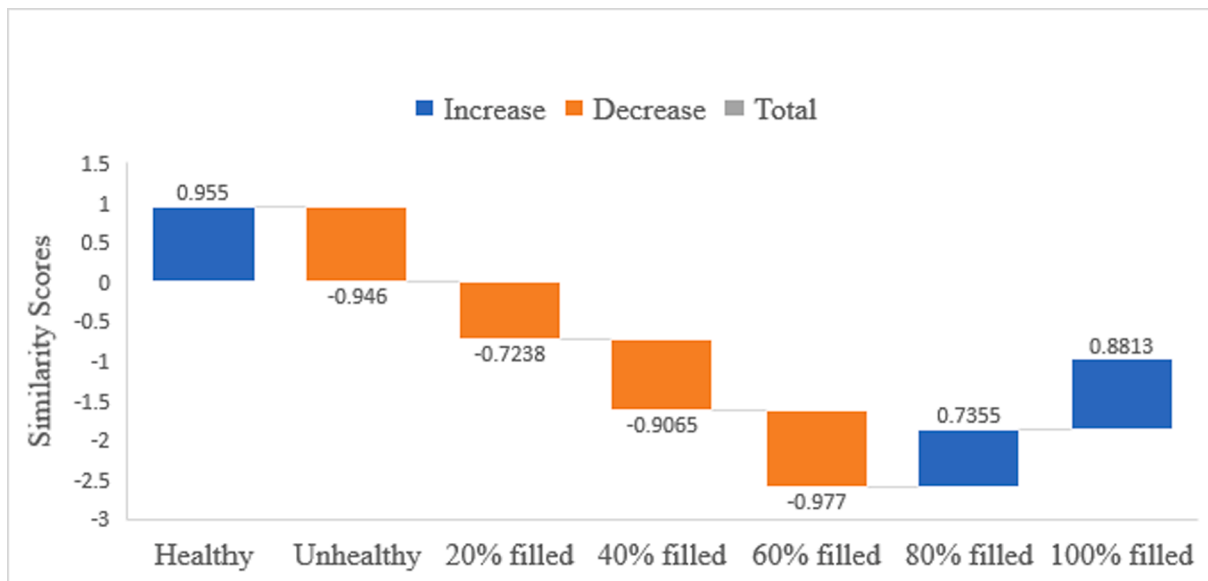


Fig. 20. The cross-correlation score transition (Healthy means a condition of no damage; unhealthy means a state of empty damage existence; 20% – 100% indicates the size of the damage length filled by debris).

signal transmission efficiency is the quantitative ratio between the power transmitted by the sidebands and the total transmitted power by the propagating wave. Ordinarily, in AM, the maximum power transmission efficiency of sidebands is about 33.30% which could be observed in the healthy condition of the structure as a transmission efficiency of 33.45% was achieved, as shown in Fig. 17. However, empty

damage (unhealthy) resulted in a sharp decrease in power transmission efficiency with a negative percentage deviation of about -5.7% but gradually increased proportionally as the percentage of debris-filled damage appreciated with a positive deviation in all the debris-filled cases. It could be observed that there is an increase in the power transmission efficiency of the sidebands in the situation of debris-filled

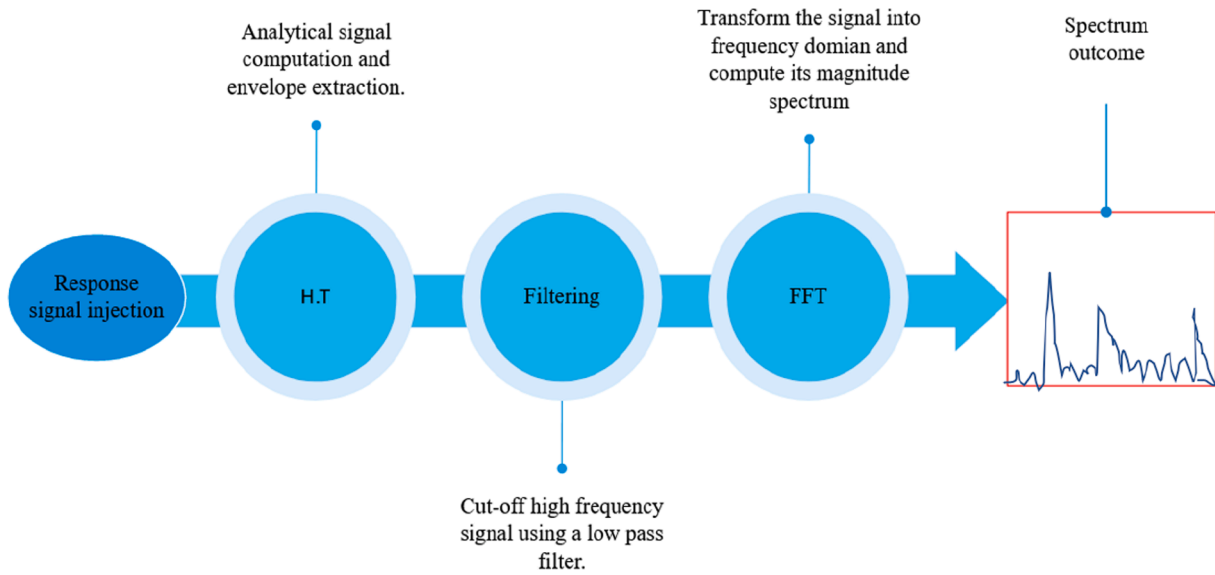


Fig. 21. The low-frequency components computation flow.

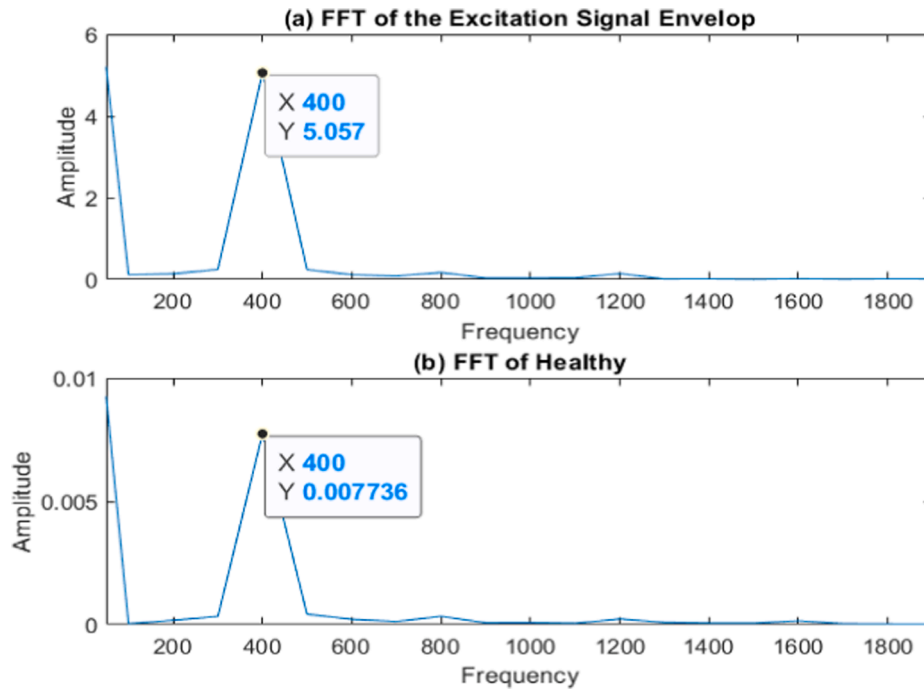


Fig. 22. The FFT of the extracted (a) Reference signal envelop (b) healthy state response signal envelop.

damage. This suggests that variations in amplitude modulation sidebands could be useful in classifying stages in debris-filled damage.

$$y = 0.8144x^3 - 1.6093x^2 + 0.9833x + 1.0385 \quad (12)$$

$$R^2 = 0.9234$$

where x = percentage of debris that filled the damage.

(d) Fig. 18a is the cross-correlation between the reference signal and the healthy structure's detrended extracted envelope signal. It could be observed that there is a strong positive correlation between the reference signal and the healthy state response signal of the structure. However, the matching peak did not occur exactly at the zero position. This could be due to the inherent inhomogeneity of the structure, as no structure is purely homogenous. Fig. 18b shows the cross-correlation

between the reference signal and the detrended extracted envelope response signal of the empty damage. It could be observed from the graph that the response signal from the empty damage is strongly uncorrelated with the reference signal. The uncorrelation situation is due to the existence of damage in the structure.

(E). In furtherance, the cross-correlation between the detrended reference signal and the response signal when the damage is gradually filled with debris was computed and plotted in Fig. 19. The similarity matching scores of the compared signals were deduced and plotted in Fig. 20. The results indicate a strong uncorrelation between the reference signal and the response signal from the damaged structure as the debris-filled percentage increases except for 80% and 100%. The uncorrelation could be attributed to the absorption and scattering effect experienced by the response signal at the damaged spot. At 80% debris-

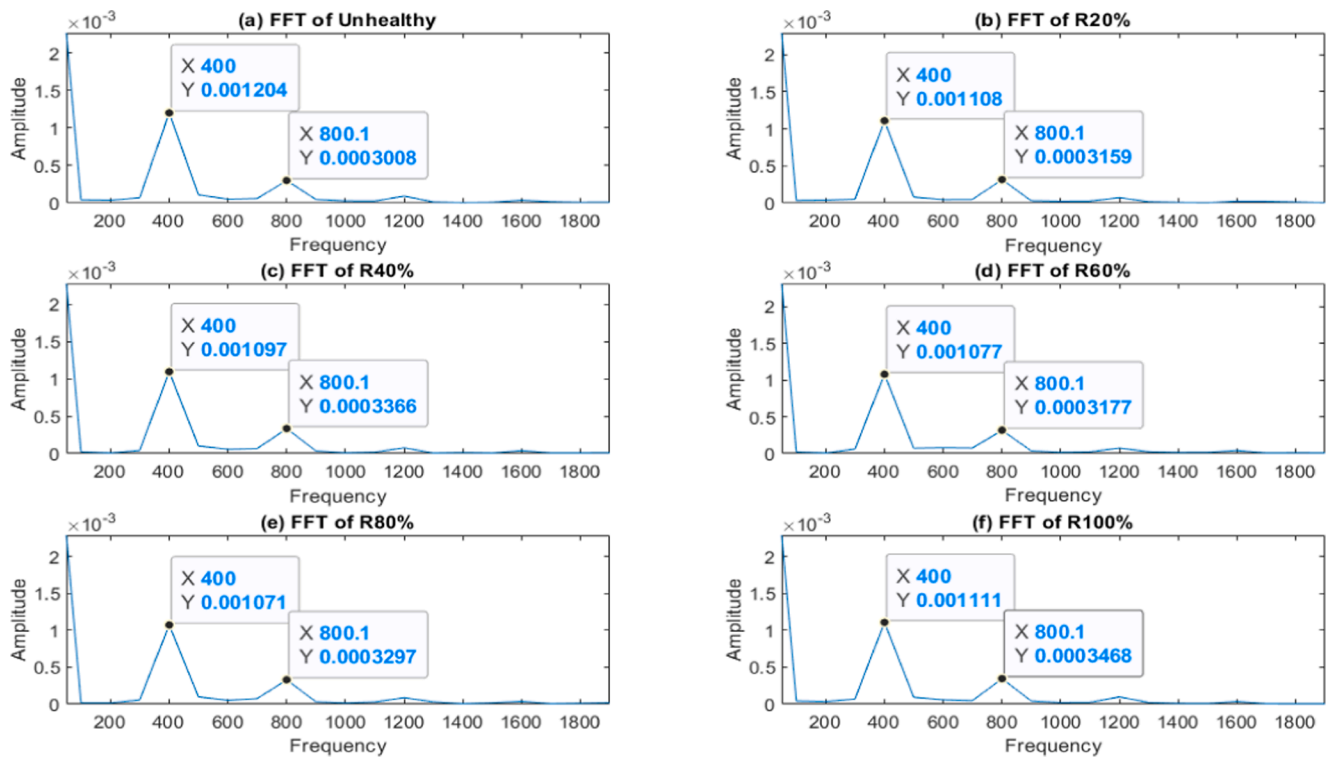


Fig. 23. The FFT of the processed low-frequency component when the debris coverage is (a) 0% (b) 20% (c) 40% (d) 60% (e) 80% (f) 100%.

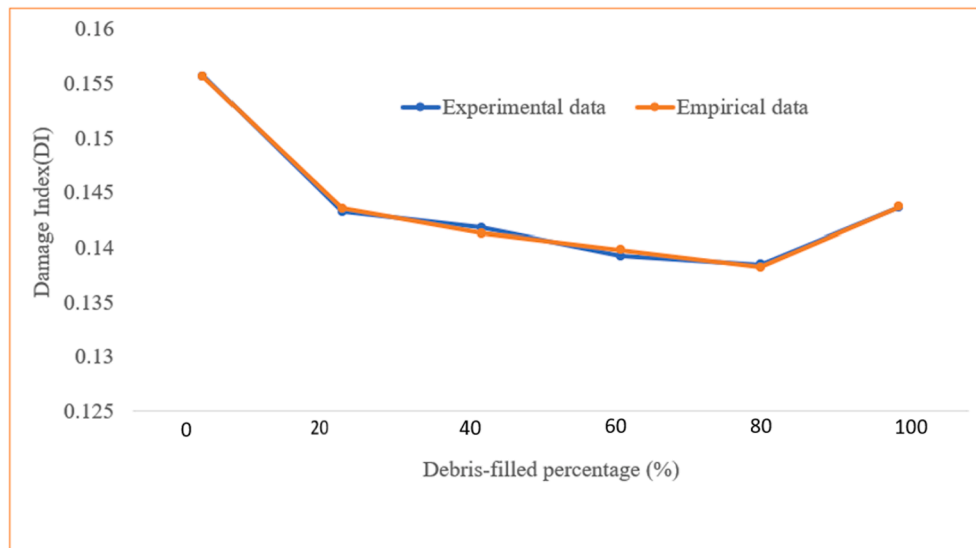


Fig. 24. Damage index for debris-filled damage of varying percentages.

filled, the remaining open length of the crack is just 8.00 mm, implying that 32 mm out of the 40 mm length of the damage is filled with debris and would offer less scattering effect to the response signal. As debris fills the damage, it creates false continuity of the structure, allowing easy passage of signals with less distortion and considering that the debris is fine particles. The results suggested that cross-correlation of detrended signal response could be useful in detecting damage and the debris-filling situation at an early stage.

(F) Since we observed that the response signal was further modulated after interaction with the damaged structure, we extracted its envelope and further analysed it. We applied a lowpass filter to cut off any existing high-frequency component, as described in Fig. 21. The spectrum of the reference signal, the healthy state (a state of no damage) response signal,

the unhealthy state (a state of empty damage) response signal and the response signal of the structure when debris fills the damage are computed and shown in Fig. 22 and Fig. 23. Interestingly, we observed that the damage caused higher harmonics ($2f_m$) of the fundamental low-frequency (f_m) component to occur, as spotted in Fig. 23. The new frequency component is still low and can only be caused by the existing damage and contributes to causing overmodulation of the response signal. The intensity of the higher harmonic varies as the percentage of debris-filled damage increases, as depicted in Fig. 23.

(g). A regression analysis was performed to describe the relationship between response signal intensity and the debris-filled damage percentage. The damage index was computed and correlated with the percentage of debris-filled damage, as shown in Fig. 24. The correlation

resulted in an empirical predictive Eq. (13). The experimental and empirical results were compared, and the mean error was determined. Based on the error result, the practical predictive model could detect an early debris accumulation much better than when it filled the damage by 100%. The absolute average percentage error of the empirical predictive model is circa 0.21, and its squared correlation coefficient value is about 0.996.

$$P = 0.2121a^4 - 0.443a^2 - 0.1102a + 0.1556 \quad (13)$$

$R^2 = 0.996$, where a is the percentage of debris-filled damage.

5. Conclusion

The pre-modulated guided ultrasonic wave interaction with varying percentages of debris-filled damage was investigated. In the study, the high-frequency carrier wave was pre-modulated with a low-frequency wave to form wave packets before being injected into the structure through the actuator transducer PZT. The modulation extent of the wave after interaction with the structure in healthy state and damage existence conditions were examined. Pitting corrosion filled with varying percentages of debris was discussed and implemented as damage to the structure (mild carbon steel plate). Analysis of the processed response signals showed that pitting corrosion damage and percentages of debris that filled damage could be detected early using a modulated wave and GWUT. The modulation extent of the wave was correlated with the damage existence conditions, resulting in an empirical predictive model Eq. (12) with an average percentage error of 1.34 and squared value of correlation coefficient of 0.9234. Similarly, the response signal of an extracted signal envelope and its analysis revealed that the existence of the damage and its varying percentage of debris-filled could cause a formation of a low-frequency component, 800.1 Hz, as in Fig. 23. The formed low-frequency component is a higher harmonic ($\approx 2f_m$) of the fundamental low frequency (f_m) wave component. Based on the healthy and unhealthy situation intensity ratio through the processed response signal envelope, another empirical predictive model of Eq. (13) was developed with an absolute average percentage error of 0.21 and squared value of correlation coefficient of 0.996. Cross-correlation of the detrended response signal and reference signal demonstrated to be a quick means to visualise and spot damage existence and its debris-filling conditions. In summary, our study approach points out a new possibility for ease of structural health monitoring (SHM) and early detection of debris-filled damage to avert the formation of grievous pitting corrosion attacks in structures of high economic importance.

CRedit authorship contribution statement

Olisa C. Samuel: Conceptualization, Methodology, Validation, Visualization, Formal analysis, Investigation, Data curation, Writing – original draft, Resources, Writing – review & editing, Funding acquisition. **Andrew Starr:** Formal analysis, Resources, Writing – review & editing, Supervision, Project administration. **Khan A. Muhammad:** Conceptualization, Methodology, Validation, Visualization, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Monitoring evolution of debris-filled damage using pre-modulated wave and guided wave ultrasonic testing (GWUT)

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