Detecting contact acoustic nonlinearity in TOFD measurements via quasistatic loading

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Abstract. In this paper, we propose a novel method to detect and quantify contact acoustic nonlinearity using conventional time of flight diffraction (TOFD) non-destructive testing (NDT) equipment, with the aim to improve the sensitivity and robustness of TOFD measurements. This new method involves applying an external cyclic quasi-static load while simultaneously taking TOFD measurements. The applied load causes modulation of contact surfaces within damaged areas of the material, which can be observed as changes in the time-domain TOFD response. Additional processing extracts any load-dependent features from the signals, allowing the identification and quantification of damage and defects that exhibit contact acoustic nonlinearity. Importantly, this new quasistatic contact acoustic nonlinearity (QS-CAN) technique maintains time-resolution and localisation capability of conventional TOFD. It is shown that the technique can differentiate between different types of damage such as fatigue cracks or voids within samples. The new QS-CAN nonlinear ultrasonic methodology is a fundamental extension to all existing nonlinear measurement techniques. It allows for the first time to use time signals captured from conventional NDT equipment to extract nonlinear material characteristics.

Introduction

Time Of Flight Diffraction (TOFD) is a commonly used ultrasonic non-destructive evaluation technique. TOFD is routinely used for the inspection of welds in low alloy and carbon steels due to its efficient and accurate sizing of defects [1]. However, there are now new generation Corrosion Resistant Alloys (CRA) such as austenitic stainless steels in use. These materials have an anisotropic grain structure which makes conventional TOFD challenging due to scattering in the material [2-5].

A similar issue exists in ultrasonic testing of composite materials, the impedance mismatch between fiber, matrix and intra laminar layers causes scattering of ultrasonic pulses which occludes actual defects. In this field, nonlinear ultrasonic methods have proven to be effective to detect material damage. However, these nonlinear methods operate almost exclusively in the frequency-domain and so sacrifice localization.

Therefore, despite suggestions that nonlinear methods might be applicable to TOFD there has been no way to reconcile time-frequency duality and preserve defect localization, a critical property of conventional TOFD measurements. In this paper we propose a novel technique based around processing of TOFD waveforms under cyclic loading conditions to extract nonlinear features of the sample entirely in the time domain.

Nonlinear Methods

Nonlinear approaches to ultrasonic testing have existed for decades [6], fundamentally these methods are based around the principle of stress-stain relationships deviating under certain conditions. When this occurs, acoustic energy traveling through the material becomes distorted and this effect can be measured.

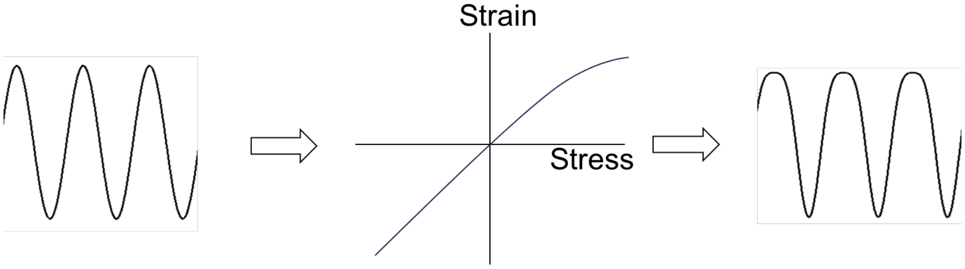

Figure 1: Nonlinearity due to deviation in stress-strain relationship in a material

Early nonlinear methods used a single excitation source, so called harmonic methods [7]. However, current methods make use of multiple excitations, known as Vibro-Acoustic Modulation (VAM). Vibro-Acoustic techniques are more sensitive to defects. In VAM a high frequency ultrasonic wave (probing wave) and a low frequency mechanical excitation (pumping wave) are used simultaneously to excite a sample. In the presence of defects, the probing wave undergoes modulation which can be detected and used as a damage index. For example, Figure 2 demonstrates how a beam with a fatigue defect can cause modulation of a probing wave when excited with low frequency mechanical vibration.

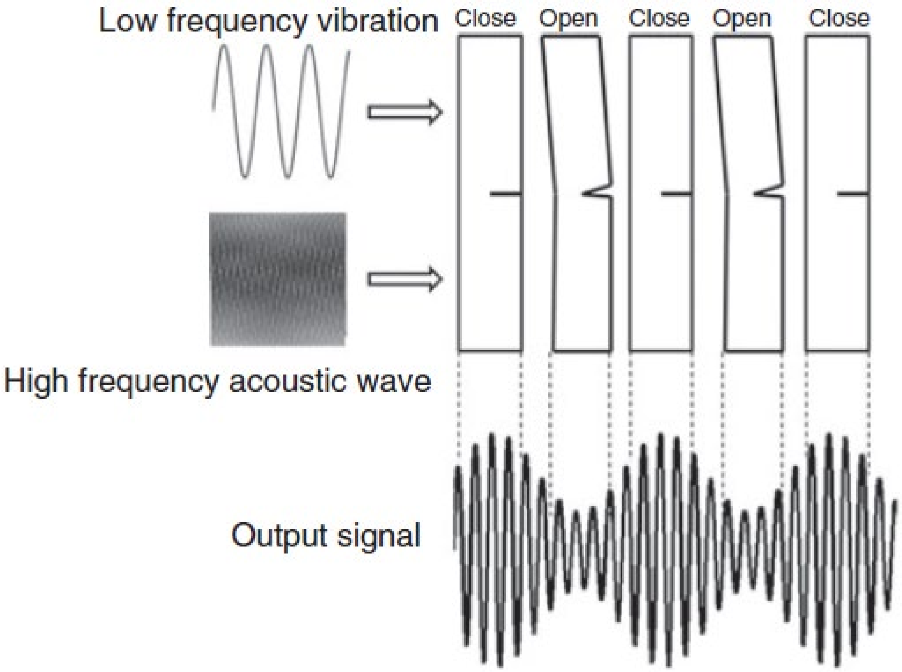

Figure 2 Example of Nonlinearity due to crack modulation in a beam [8]

Quasi-Static Approach

The purpose of the low-frequency pumping wave is simply to modulate any mechanical defects within the sample [9], actual information about the nonlinearity of the material is encoded onto the probing wave. In theory, this means that the frequency of the pumping wave can be chosen arbitrarily, provided it is much lower than the probing wave [10, 11].

However, due to practical considerations the pumping frequency is often very near structural resonant frequencies to maximize excitation amplitudes [11]. This approach is very sensitive to the modal response of the system and other amplitude dependent nonlinear effects occur at these resonance points.

Therefore, instead of applying this external forcing vibration by a transducer we propose using a much slower, but higher amplitude external load. This applied stress is still well within the nondestructive range for the material. In this paper the external quasi-static load is applied by a tensile testing apparatus, but this doesn't preclude practical approaches. For example, in pipeline or tank inspection, the external load can be applied by varying levels of pressurization. Otherwise, opportunistic measurements under different loading scenarios may be feasible for civil structures. As will be shown in this paper, a stress fluctuation of less than 1% of the failure stress was sufficient.

Quasi-Static TOFD

Expanding on the general quasi-static idea, the quasi-static TOFD (QS-TOFD) concept was developed. In this proposed method a sample is excited using a conventional TOFD system under various quasi-static loads. Then, through signal processing it is determined if any features in the TOFD waveform exhibited load dependent behavior. Since any load dependent variation in the waveform is indicative of nonlinearity in the material, this can be used to locate and infer the type of damage. Importantly, no frequency-domain transformation is used, and hence damage local information is preserved.

Methodology

The proposed method was investigated using various aluminum beams, which can be seen in Figures 3-5. The dimensions of the beams are 40x40x250mm and made from 6061-T6 alloy. The large through-thickness was chosen so that the distance between lateral wave and backwall was maximized. The induced damage was drilled holes as well as cyclically grown fatigue cracks. An *Instron Series 5900 Universal Testing System* was used to apply load to the specimens. The setup is shown in Figure 6.

Table 1 details the naming convention and the samples used in testing. In both fatigue samples the crack was grown to approximately half width (20mm). A 45-degree v-notch was used as the crack initiation point, in the F1 sample this notch was 1mm deep and for the F3 sample it was 3mm. Images of the samples are provided in Figures 3-5. A 3D printed fixture was used to hold the transducers and wedges in place over the defect location. A Sonopod acquisition system was used to measure the TOFD waveforms. The instrumentation configuration is provided in Table 2.

Table 1 Names and Descriptions of Samples

Sample ID	**Description**
P1	Pristine bar
SHD20	2mm diameter 20mm offset drilled Hole
F1R	20mm fatigue crack, measured as root crack
F1S	20mm fatigue crack, measured as surface crack
F3R	20mm fatigue crack, measured as root crack
F3S	20mm fatigue crack, measured as surface crack

Table 2 Equipment Used and TOFD Configuration

Acquisition System	Sonomatic Sonopod + Laptop
Transducers	5 MHz 6.25mm Olympus C543-SM
PCS	55mm
Angle in Material	48.3 Deg (Using ST1-45L-IHC Wedges)
Pulse Voltage	200V
Pulse Time	100 ns
HPF	2.5 MHz
LPF	10 MHz
PRF	20 Hz
Gate Start	13 us
Gate Width	17 us
Gain	Varies (25-35dB)
Number of Samples	1000

Table 3 Mechanical loading parameters

Max Load	2500 N
Min Load	25 N
Max Compressive Stress	1.56 MPa
Min Compressive Stress	0.0156 MPa
Loading Rate	100 N/s
Load Profile	continuous linear ramp
Load/Unload Cycles	Approx. 5

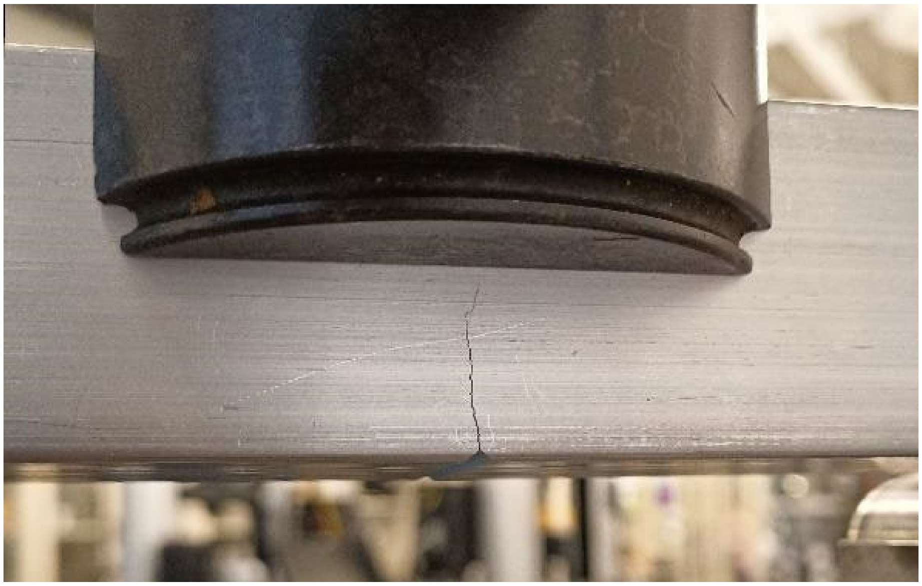

Figure 3 Sample with fatigue crack grown under cyclic loading

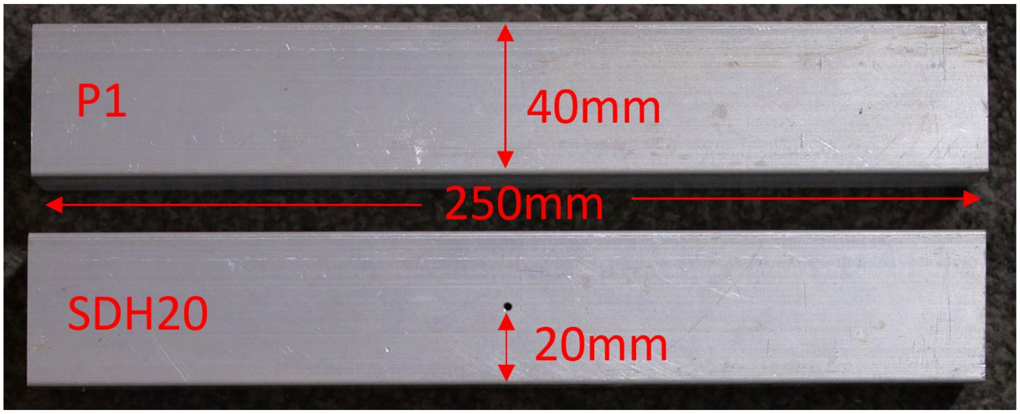

Figure 4 Image of samples with external dimensions listed

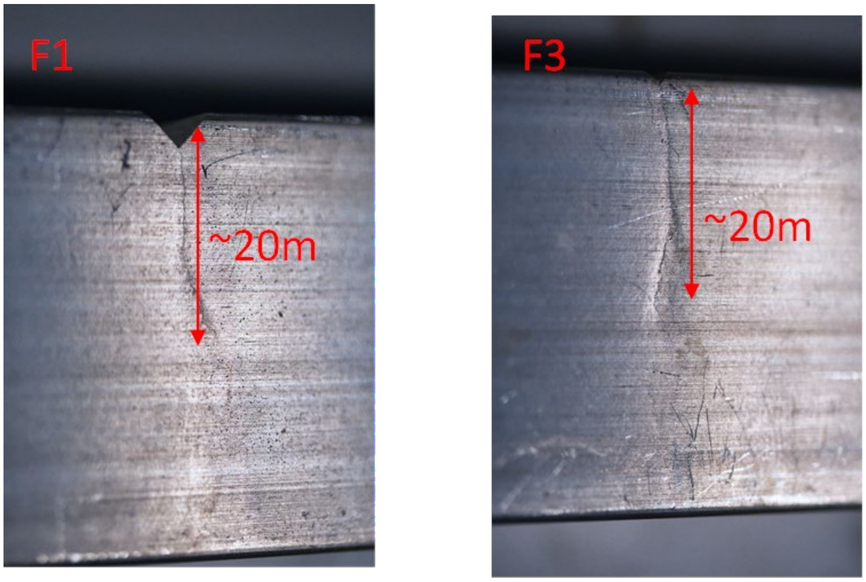

Figure 5 Close up detail of fatigue defects

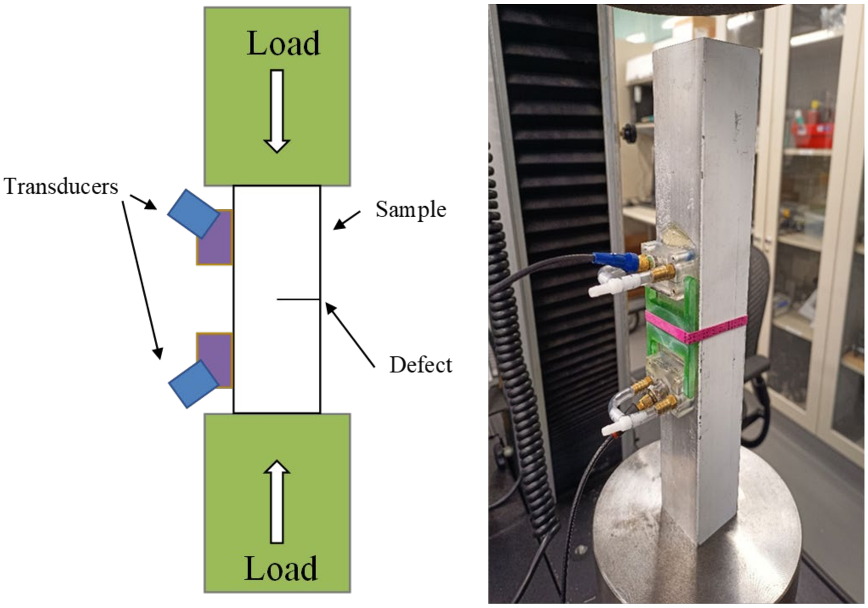

Figure 6 Image of sample in test fixture

Signal Processing

The processing requirements for the new method are significantly more involved than conventional TOFD. Broadly speaking, it is necessary to add another dimension to the scan data. An array of measurements at different loads are required for each point. Then, the average TOFD response is computed by taking the mean of the array of these measurements. Each A-scan is subtracted from the mean leaving the resultant residual plots which contain the load-dependent behavior. The processing chain is shown pictorially in Figure 7.

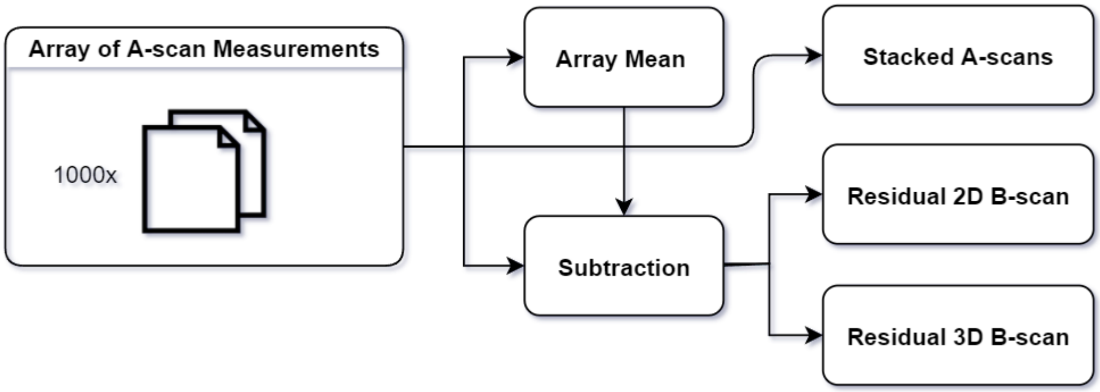

Figure 7 Data processing steps for proposed method

Results

The output of the processing are three types of figures, these are:

Stacked A-scans:

- Each individual A-scan was plotted on a single chart, giving a representation of stacked time histories which shows any variability in A-scan signals due to the changing quasi-static loading

B-scan of Residual:

- Each A-scan is subtracted from the average A-scan, leaving the difference between the current A-scan and the average A-scan at the current slice.

B-scan of Residual (Surface Plot):

- As before, but a 3-dimensional surface plot

The residual plots are the metrics of interest, a variation in this property means the TOFD waveform is dependent on the applied load. Since load-dependent acoustic response is nonlinearity, this is direct measurement of nonlinearity in the time-domain. Importantly it is also demonstrated how this measurement can be done by use of conventional UT equipment and does not require specialized hardware or high bit-depth ADCs.

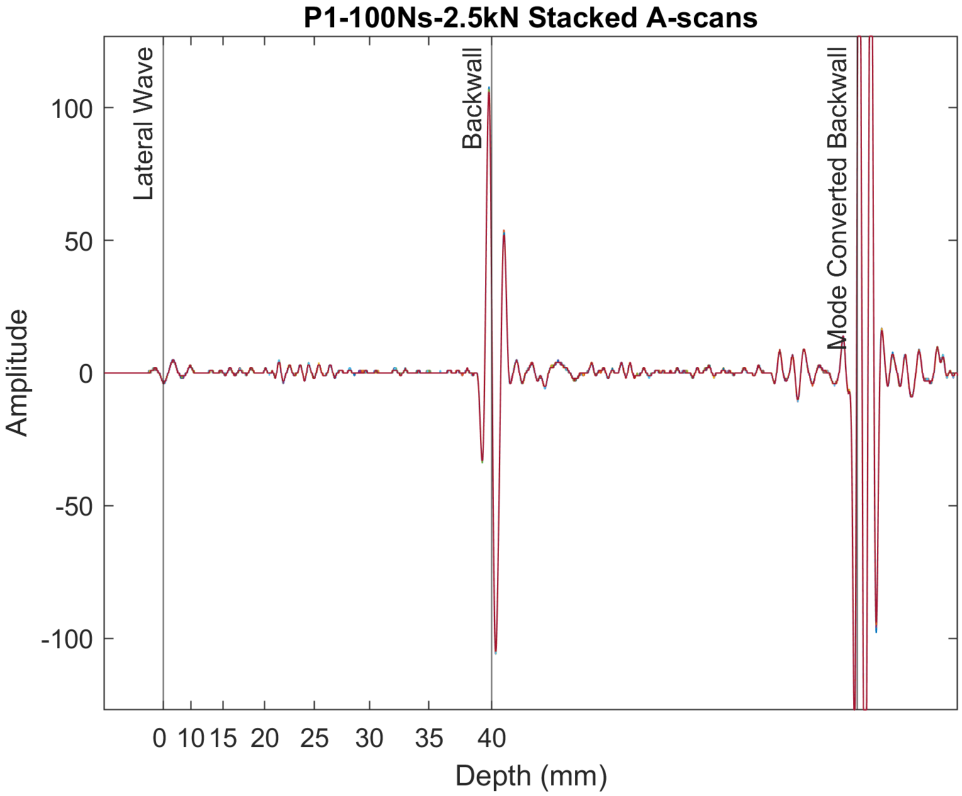

Figure 8 Pristine Sample

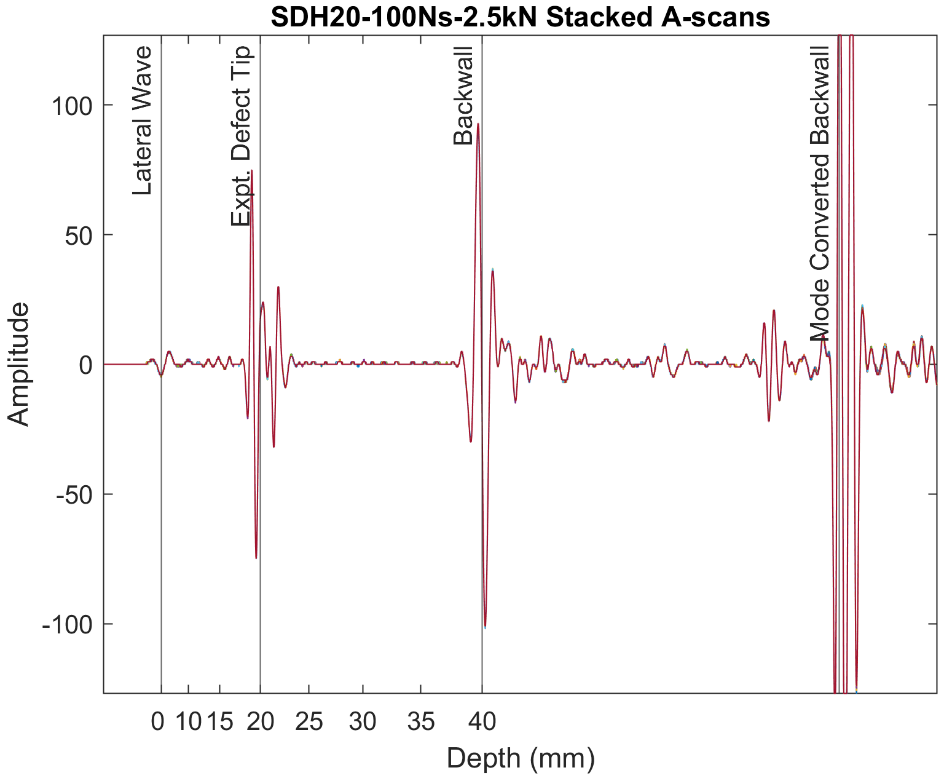

Figure 9 20mm Offset Side Drilled Hole

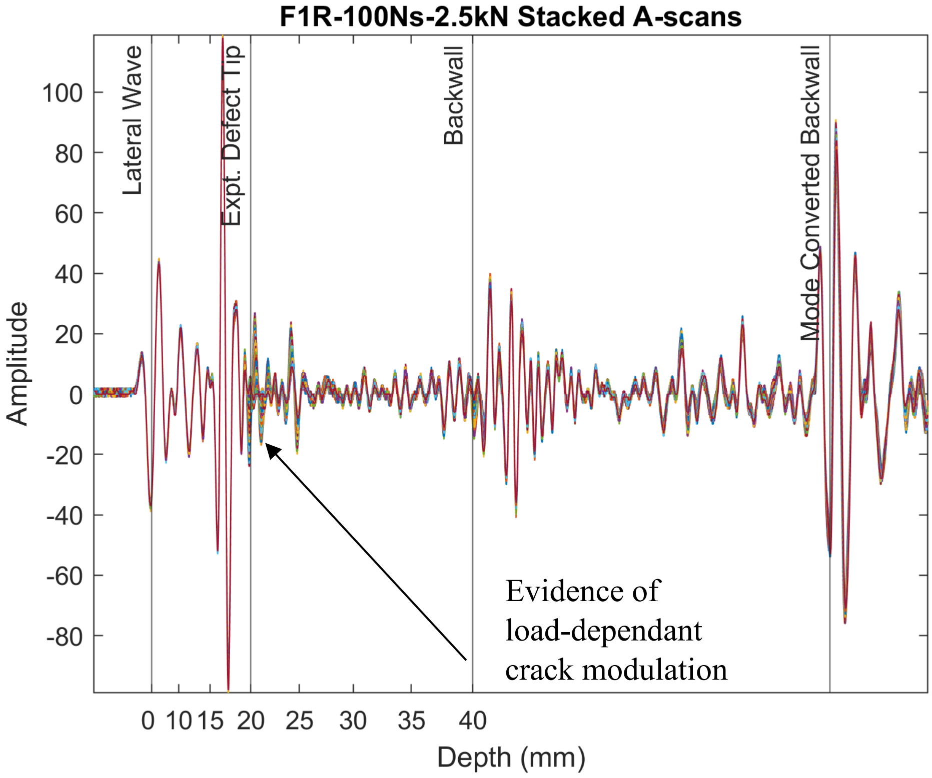

Figure 10 Fatigue Sample 1 as Root Defect

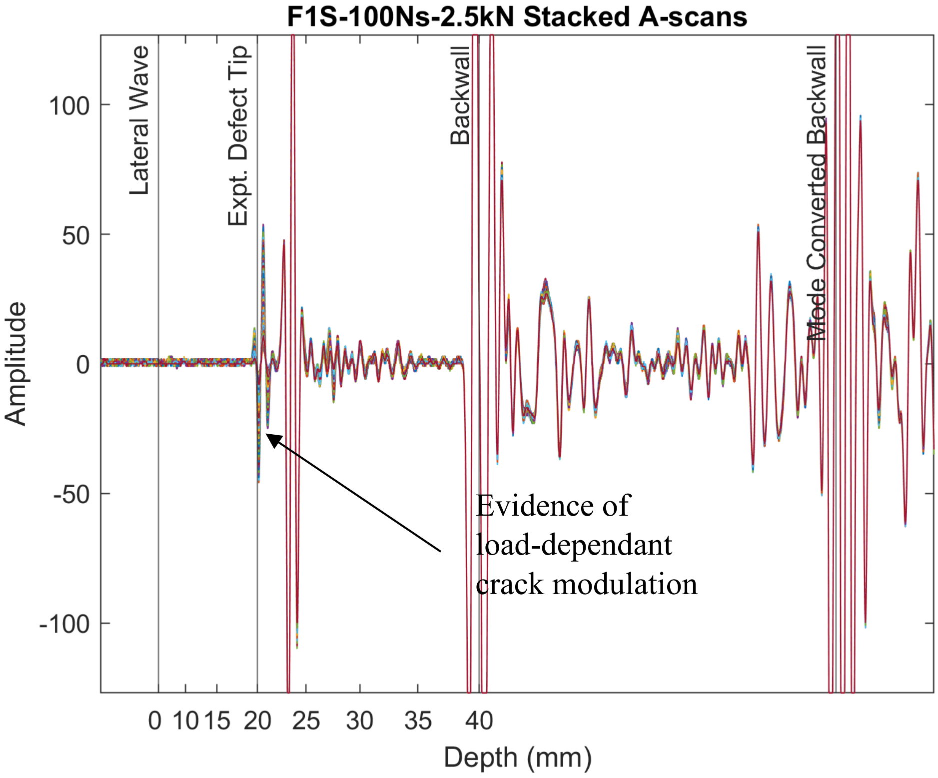

Figure 11 Fatigue Sample 1 as Surface Defect

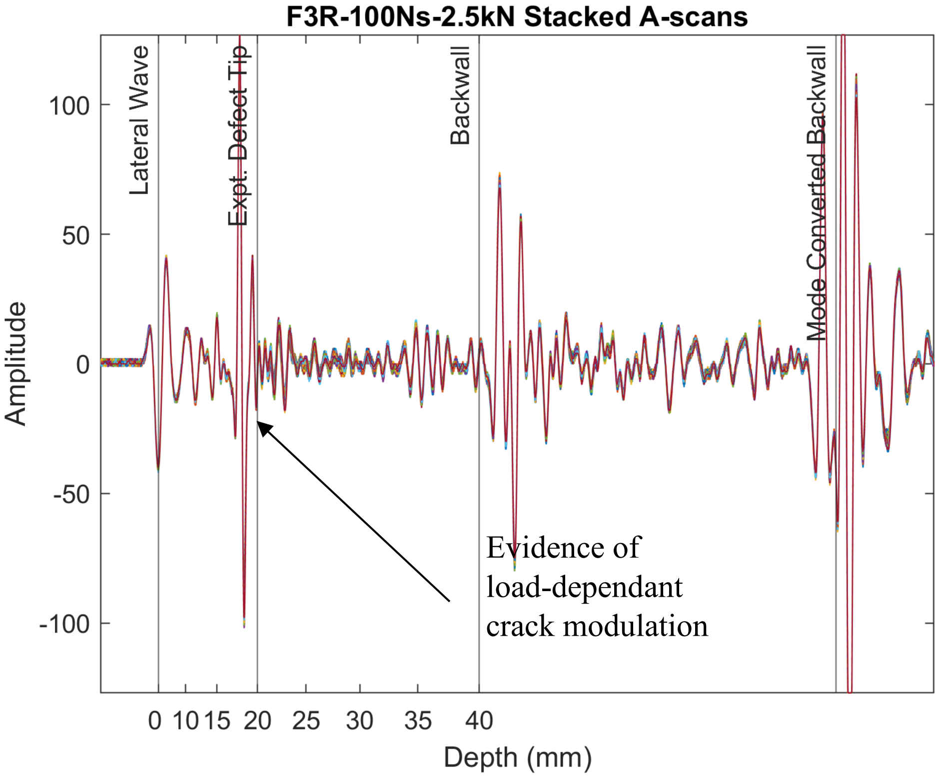

Figure 12 Fatigue Sample 3 as Root Defect

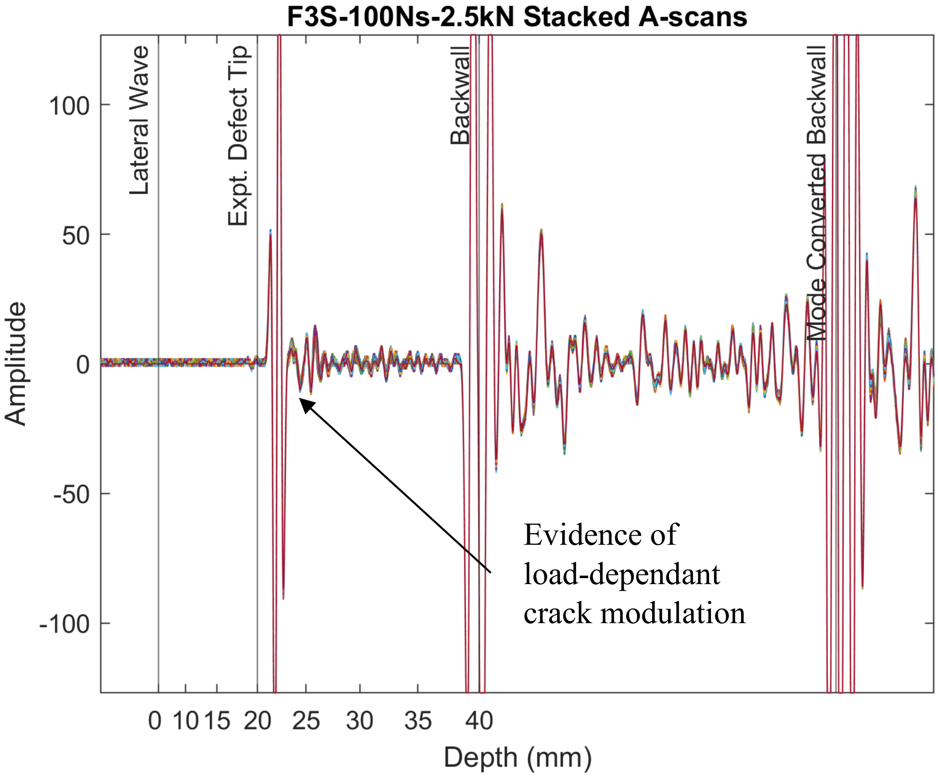

Figure 13 Fatigue Sample 3 as Surface Defect

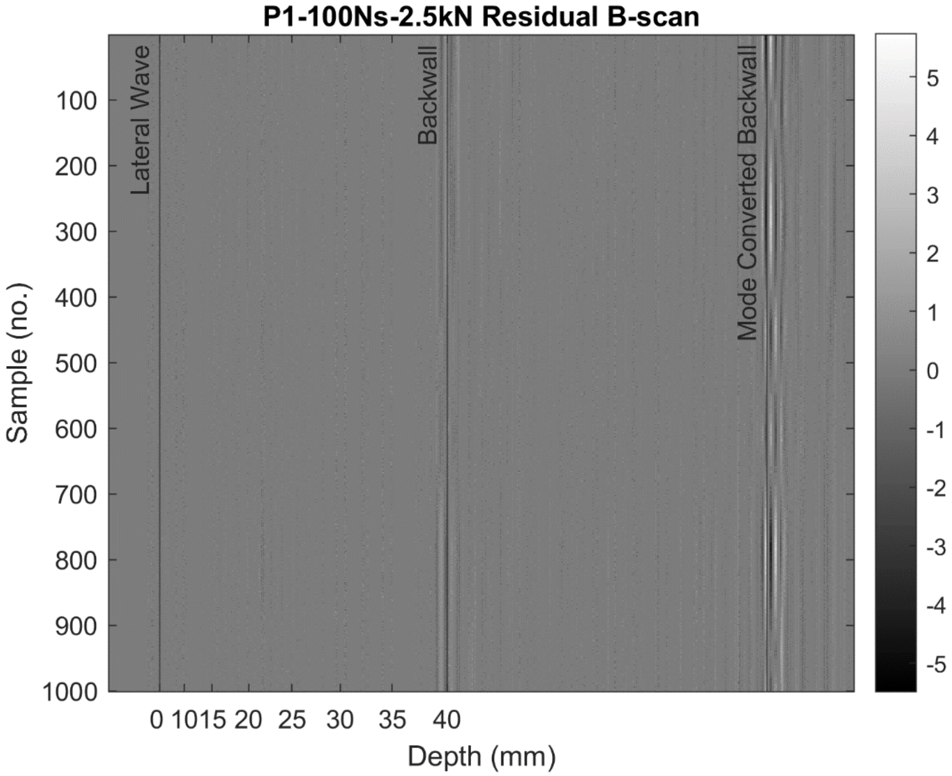

Figure 14 Pristine Sample (Residual B-scan)

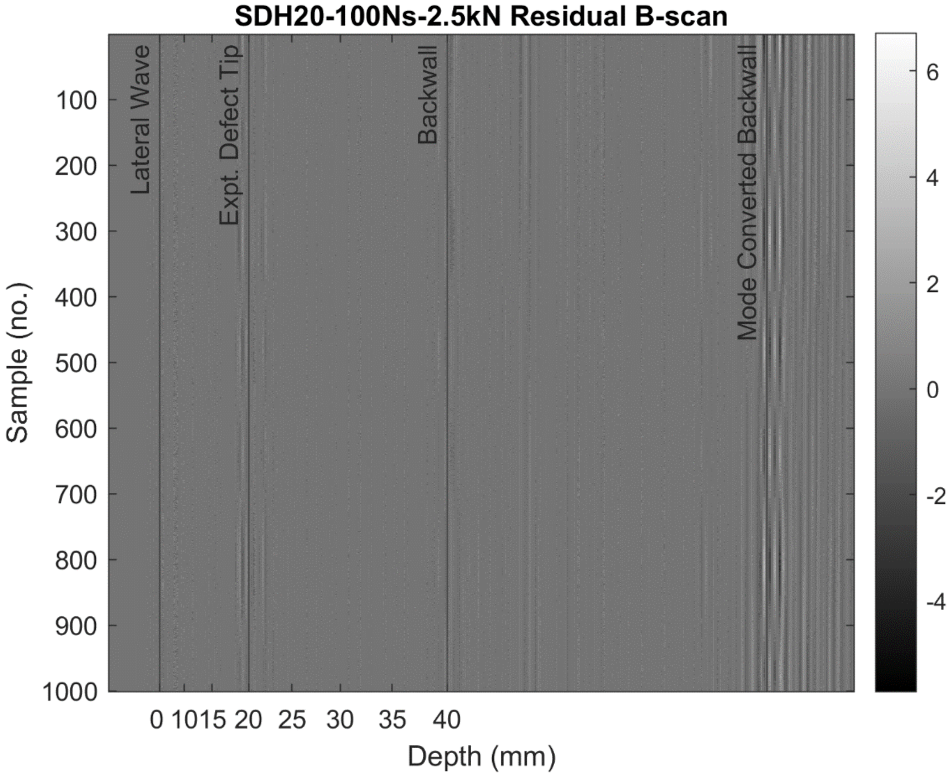

Figure 15 20mm Offset Side Drilled Hole (Residual B-scan)

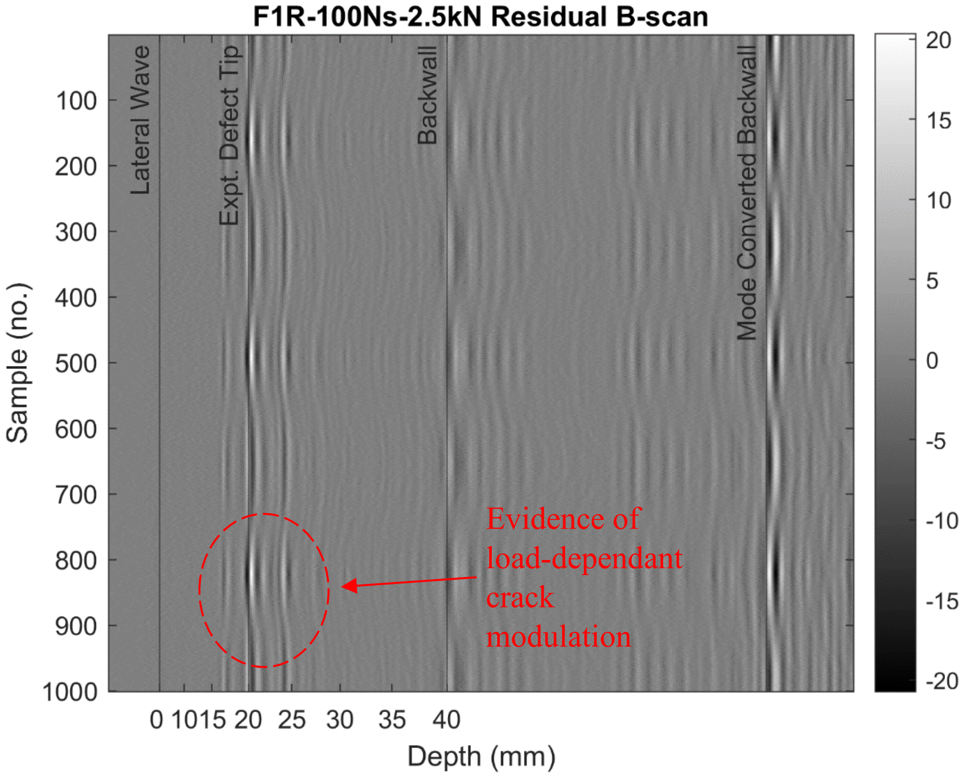

Figure 16 Fatigue Sample 1 as Root Defect (Residual B-scan)

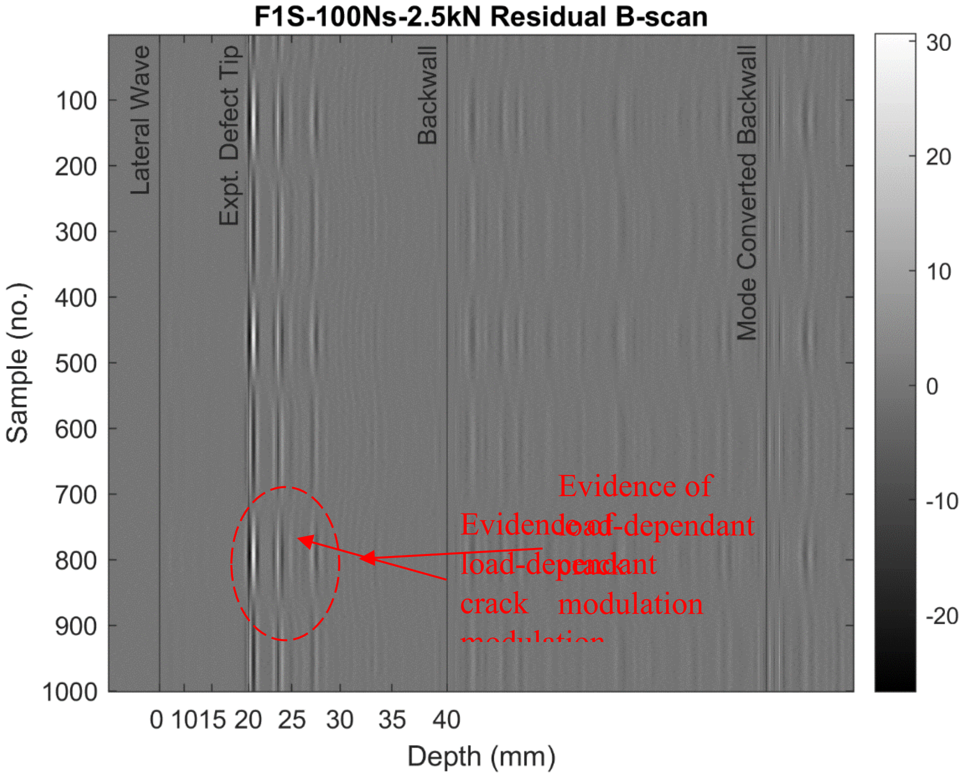

Figure 17 Fatigue Sample 1 as Surface Defect (Residual B-scan)

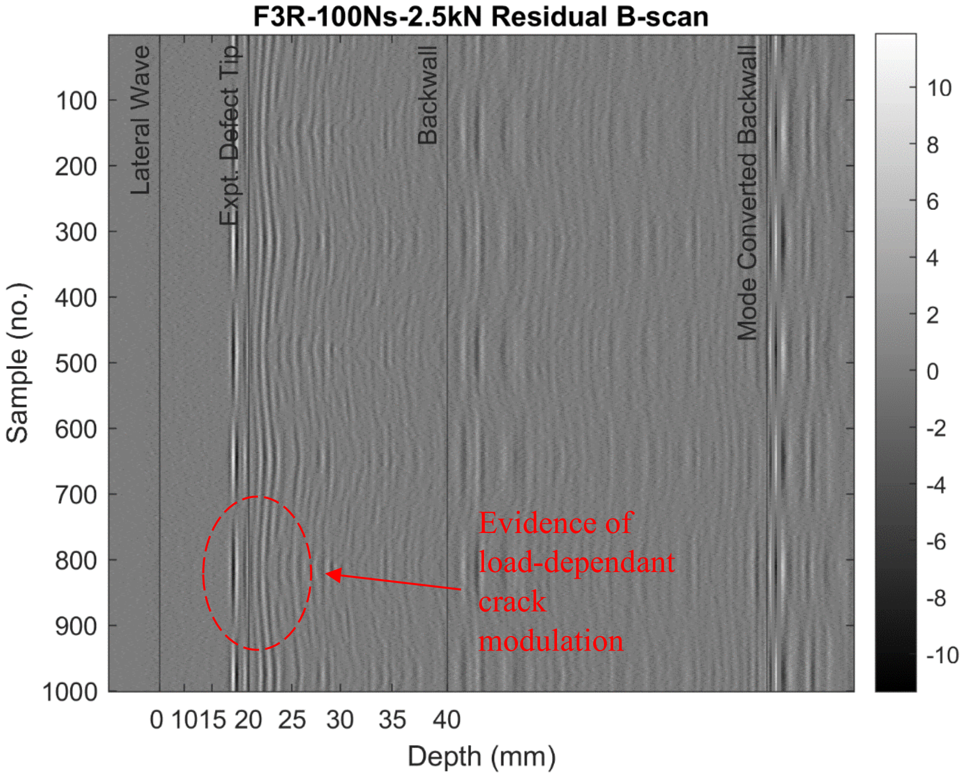

Figure 18 Fatigue Sample 3 as Root Defect (Residual B-scan)

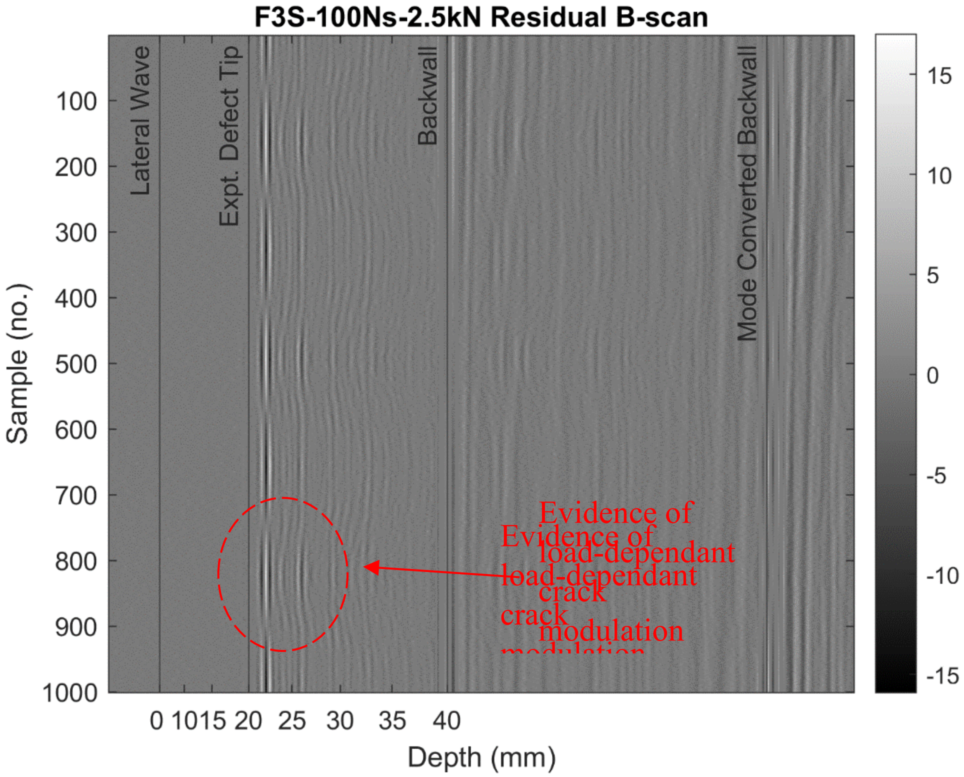

Figure 19 Fatigue Sample 3 as Surface Defect (Residual B-scan)

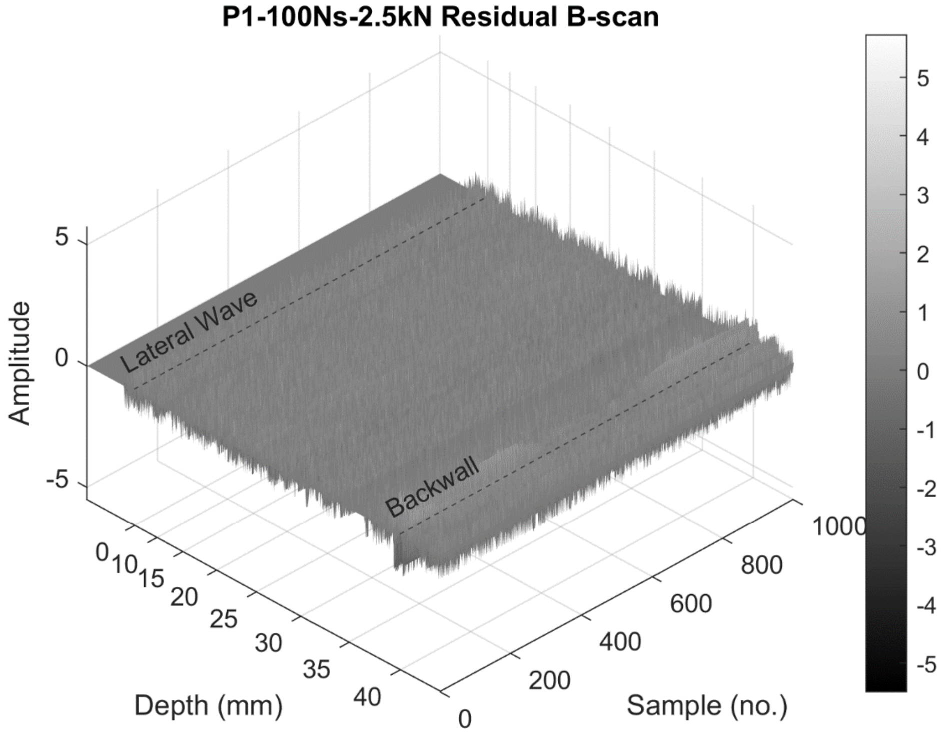

Figure 20 Pristine Sample (Surface Plot)

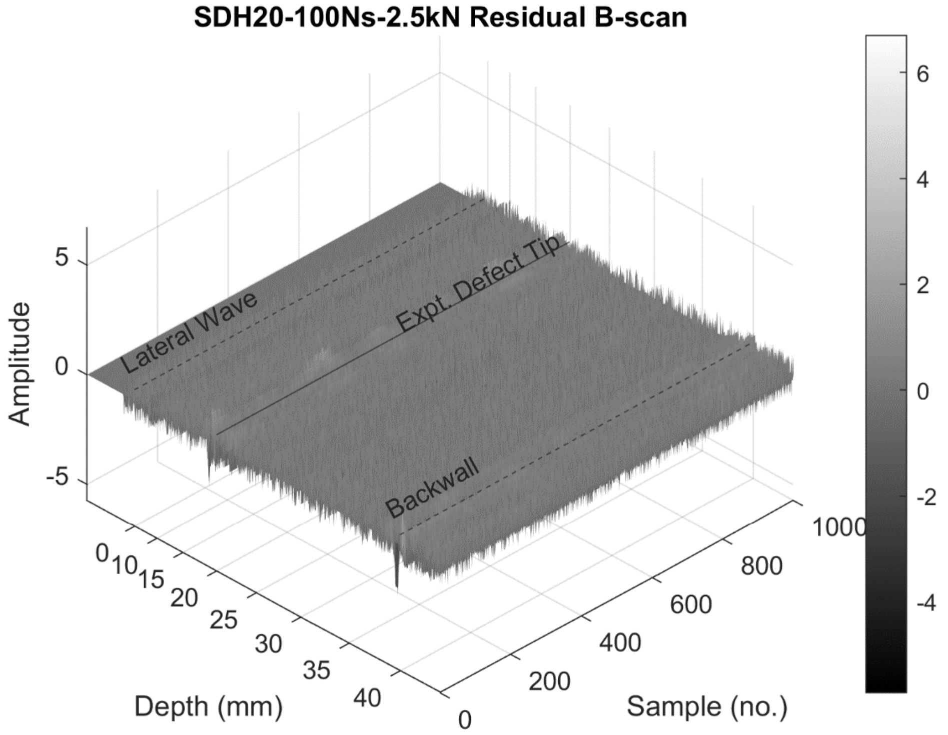

Figure 21 20mm Offset Side Drilled Hole (Surface Plot)

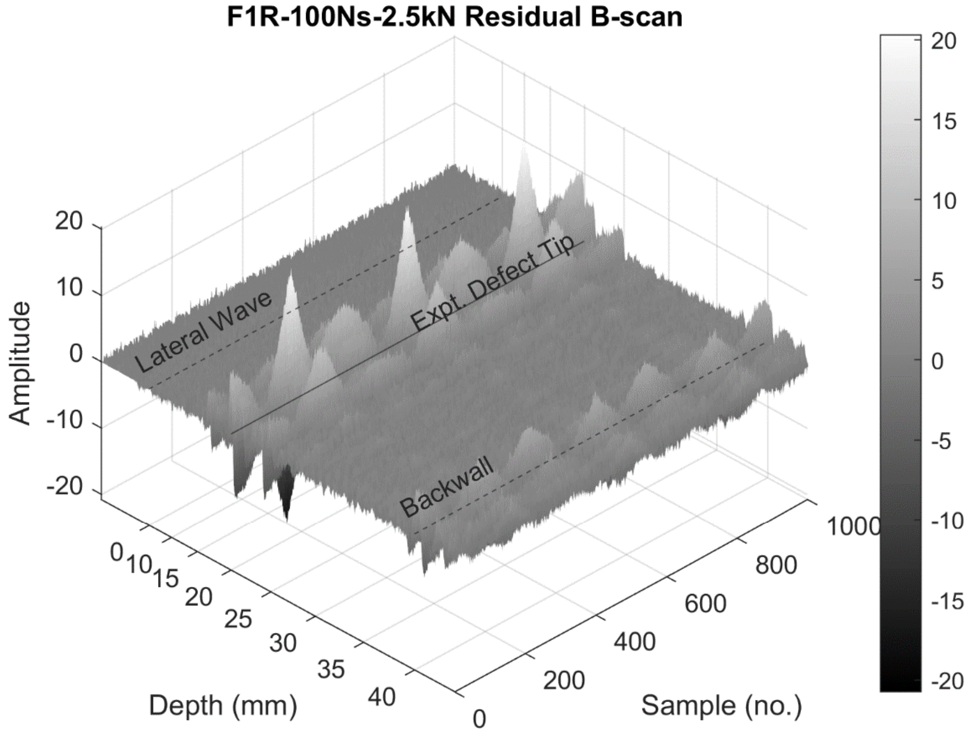

Figure 22 Fatigue Sample 1 as Root Defect (Surface Plot)

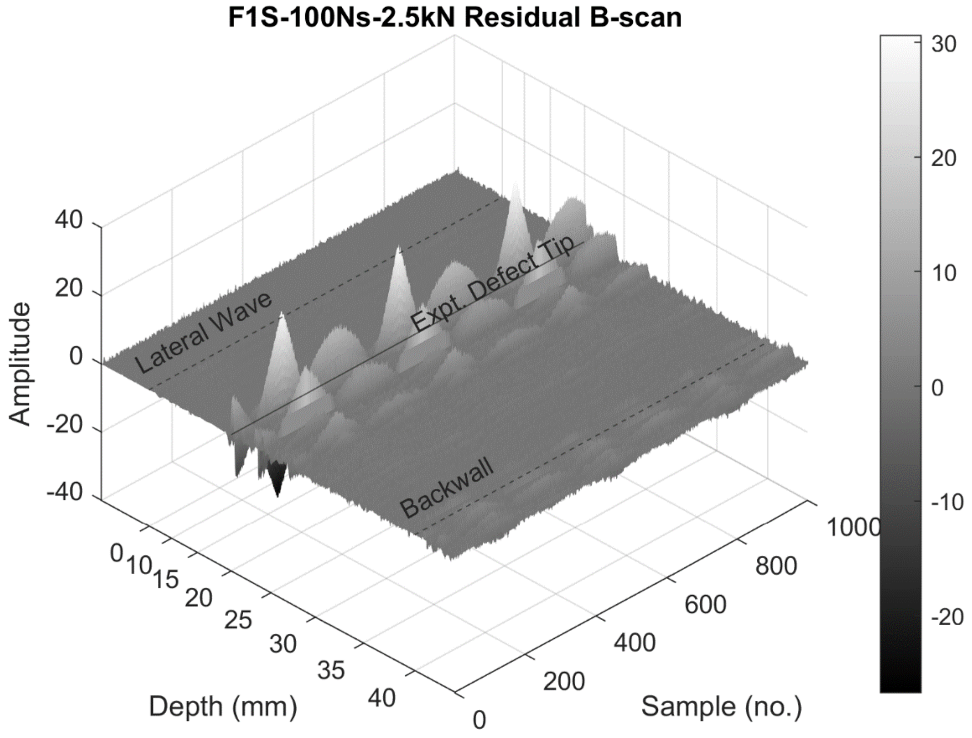

Figure 23 Fatigue Sample 1 as Surface Defect (Surface Plot)

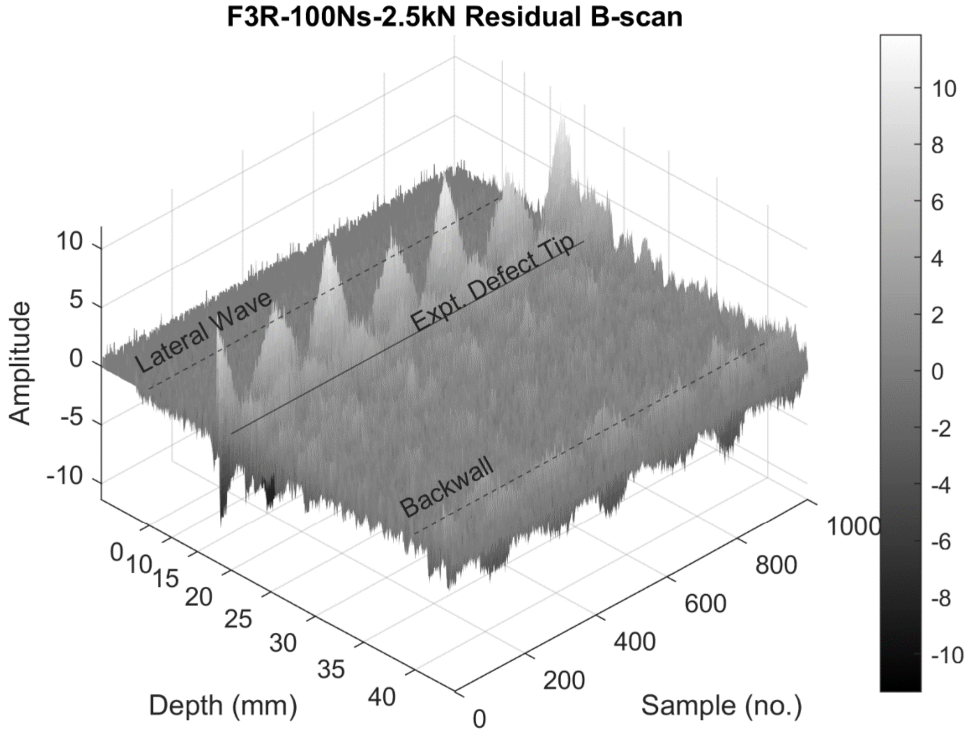

Figure 24 Fatigue Sample 3 as Root Defect (Surface Plot)

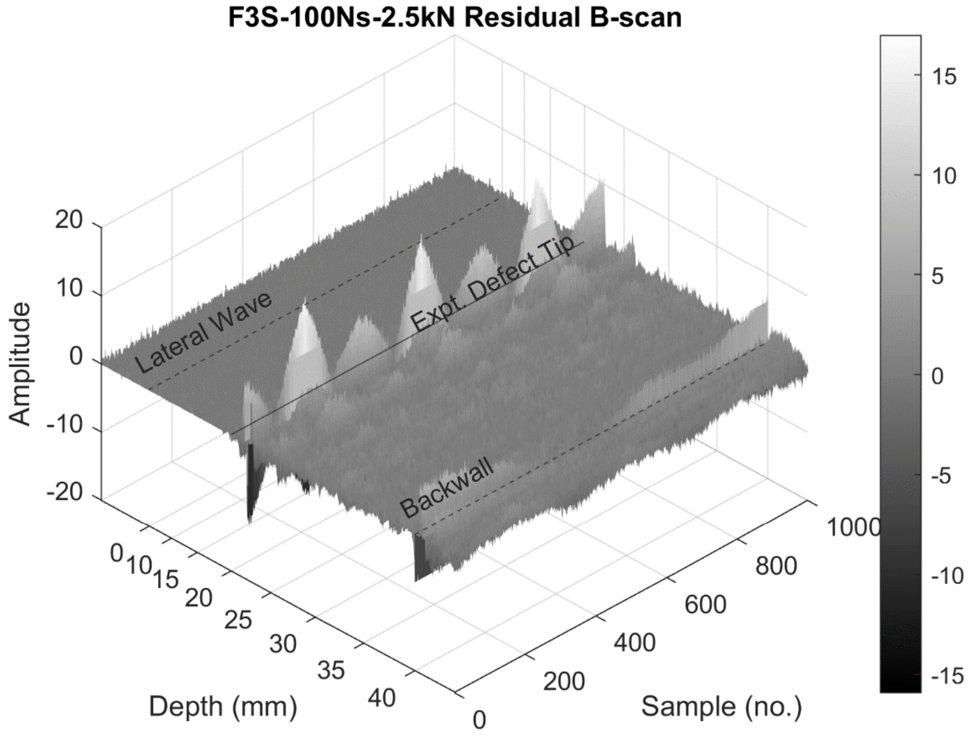

Figure 25 Fatigue Sample 3 as Surface Defect (Surface Plot)

Discussion

Starting with the pristine and the side drilled hole samples in Figures 8 and 9 we can see a typical TOFD waveform. The main features (LW, Defect, BW, MCBW) can be seen clearly. Recalling that there are 1000 stacked A-scans in these figures, very little sample to sample variation in both the Pristine and SDH20 measurements is seen. It is observed that each A-scans lies atop one-another. This is the expected behavior for these samples as there is no hypothesized mechanical phenomena that should have a load dependent effect. For the SDH20 sample the diffracted signal occurs exactly where it is expected based on the geometry of the sample.

Considering now the fatigued samples (Figure 10 to Figure 13) We can see variation in these stacked A-scans which indicates that the defect behavior is load-dependent. These effects are most evident around the expected defect tip and well as the MCBW in the case of the root defect configuration. This supports the hypothesis that these fatigue defects are experiencing load-dependence.

This observed load dependence is more easily observed in the B-scan residual plots. (Figure 14 to Figure 19). Considering the pristine and SDH20 samples, we can see no significant modulation around the lateral wave, defect or backwall. However, there is a small about of modulation present in the backwall echo of both samples. This is unexpected and it is not clear what this is caused by, especially considering the lack of this modulation in the lateral wave.

Again, the fatigue samples exhibit strong modulation around the defect and backwalls, with the root defect configurations having stronger effects in the MCBW. There is no evidence of this load-dependent effects in the lateral wave. Although, it should be noted that the lateral wave is not visible in the surface defect setup (as expected). The magnitude of this modulation is similar between fatigue sample 1 and fatigue sample 3.

Figure 20 to Figure 25 show the same data as the previous sets, but as surface plots. It is easier to see the modulation around the tip of the crack and the backwall. It is observed that the modulation is linearly proportional to the applied load by looking at the perfectly triangular peaks in Figure 22 to Figure 25. However, there is some asymmetry in seen in Figure 23 and Figure 22.

These results provide strong evidence that the TOFD waveform response of fatigue defects are sensitive to applied loads. Hence, this is direct detection and measurement of nonlinearity from contact acoustic nonlinearity. It's shown that under the same loading conditions the pristine and SDH samples did not exhibit strong modulation under load whereas fatigue defects did.

Therefore, this technique is proposed as a method to detect and quantify the difference between linearly behaving defects (voids) and defects that exhibit load dependence (fatigue cracks). It is also shown that this approach can be implemented with a standard UT system at 8 bits of vertical resolution and does not require specialized, high bit-depth measurement systems.

Comments on Practicality

It is recognized that the specific methodology shown here under tightly controlled laboratory conditions would be difficult to transfer to practical applications. The need to apply the controlled loads and take many measurements at different loads would make this impractical in a time-constrained environment. However, noting that the applied stresses are quite small compared to the material strength, this technique could be implemented by leveraging varying loads that are present in many applications.

For example:

1) A pipeline could be measured in both an in-service and out of service condition, the load variation in this case would be much more than 1% used here.

2) A continuous monitoring system could be implemented on a specific area of concern; load variations would be recorded alongside UT data and post-processing done to find correlations.

3) This technique could be applied to historical data, even if the loading conditions of previous measurements were not known any variation would suggest follow-up study.

Conclusions

In this paper a novel method to detect contact acoustic nonlinearity in a TOFD measurement was presented. The method uses an external cyclic quasi-static load to modulate mechanical defects within the sample. A series of TOFD measurements is taken simultaneously with the applied load. This data is then processed to determine the average TOFD response and the residual, which encodes any load-dependent nonlinear behavior. It was found that the pristine sample, as well as the side-drilled hole sample did not exhibit significant residual component. In contrast, both fatigue samples exhibited strong nonlinearity as indicated by the residual plots at locations near the defect tip. It is hypothesized that this is due to minute changes in the contact surfaces at the crack interface under different loads. Therefore, it is suggested that this method may be used to detect contact acoustic nonlinearity whilst preserving the time-domain locality.

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