ULTRASONIC DETECTION OF CRACKS IN A COMPLEX AIRCRAFT STRUCTURE USING A LOCAL CORRELATION METHOD FOR SIGNALS FROM A MOVING TRANSDUCER

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Abstract. A significant challenge in nondestructive evaluation is the ability to discern signals that are either closely spaced or superimposed in time. A novel feature extraction methodology is proposed where a series of signals from a moving transducer are first accurately aligned to a primary part feature and subsequently analyzed within multiple time gates for shifting signals associated with the defect. The local correlation method functions to detect the relative shift of signals in time for adjacent transducer locations due to differing echo dynamics from cracks and part geometries. Benefits of this method were demonstrated for multiple aircraft structure applications.

INTRODUCTION

In ultrasonic nondestructive evaluation (NDE), a significant challenge is the ability to distinguish multiple signals from differing sources, where one signal may originate from a defect and a second from a geometric feature in a part. This problem becomes particularly challenging when these signals are either closely spaced or superimposed in time. This problem has been observed for a variety of inspection locations in aging aircraft structures since these components were not intended for inspection. A case study is the vertical leg structural component shown in Figure 1. The fastener sites of interest are in locations of limited accessibility from the bottom surface of the wing and contain fasteners with sealant. Due to limitations with existing NDE capability and the potential teardown costs required for more accurate inspections, the United States Air Force is interested in the development of improved ultrasonic techniques for the detection of fatigue cracks emanating from aircraft holes containing fasteners in these locations.

For this case study, three general classification problems can be identified. The first problem concerns the presence of multiple paths for the same geometric reflector. Due to the complex vertical leg structure and depth of the hole locations relative to the transducer, multiple paths for the specular reflection from the hole can occur. Given their location in time, coherent noise due to secondary specular reflection signals can interfere with near crack signals. The second problem concerns multiple geometric features in close proximity that produce ultrasonic signals that are difficult to distinguish. For the problem of holes containing fasteners with sealant, under certain interface conditions, ultrasonic waves that propagate into and reradiate from the fasteners can be significant in magnitude and can occur at similar times of flight as reflected waves from a far crack. The third problem considers the additional challenge to detect the condition when these multiple signals are both present and superimposed.

Previously, measurement model were developed and validated for this class of problem [1]. In addition, automated signal classification algorithms have been developed and validated for laboratory samples [2]. However, due to these three problems primarily observed under in-field conditions, there is a need for new ultrasonic signal features for improved classification. The objective of this work is to investigate the use of multidimensional signal processing in order to distinguish crack signals from signals associated with the part geometry. A novel feature extraction methodology is proposed where a series of signals from a moving transducer are first accurately aligned to a primary part feature and subsequently analyzed within multiple time gates for shifting signals associated with the defect. The proposed local correlation method functions to detect the relative shift of signals in time for adjacent transducer locations due to differing echo dynamics from cracks and part geometries. Benefits of this method are demonstrated for the three aircraft structure case study problems.

CHARACTERIZING MULTIPLE SIGNALS IN UT NDE

A significant body of prior work has examined the subject of characterizing multiple signals in ultrasonic NDE. Initially, expert operators with hand scanning techniques used the concept of echodynamics for rudimentary signal classification and defect sizing, where the changes in amplitude and time of flight of signals were analyzed with respect to transducer motion. With the advent of automated scanning and imaging systems, the capability to accurately acquire and display echo-dynamic curves and B-scan images provided for improved signal interpretation and defect characterization. With the availability of scanning and imaging systems and advances in computational processing speed, enhanced post-processing methods for images were developed. For example, the synthetic aperture focusing technique (SAFT) has been applied to the reconstruction of image data for improved defect identification. ALOK (Amplituden Laufzeit Orts-Kurven), a method that incorporates both the amplitude and transit time dynamic curves, was developed for noise elimination and flaw reconstruction [3]. Phased array transducers also offer unique capabilities in advanced beam-forming and self-focusing with respect to conventional transducer design for improved inspection capability.

To address the increasingly complex data interpretation problem for inspectors in ultrasonic NDE, the application of automated signal classification (ASC) algorithms has also been investigated. For complex multiple signal classification problems, several approaches have been proposed that extract key features from signals that vary with transducer position. The use of the rise dynamics of the amplitude plot was proposed by Rose et al. for classification of cracks, porosity, and slag in welds [4]. In addition to amplitude dynamics, the variation of the principal components of adjacent signals has been

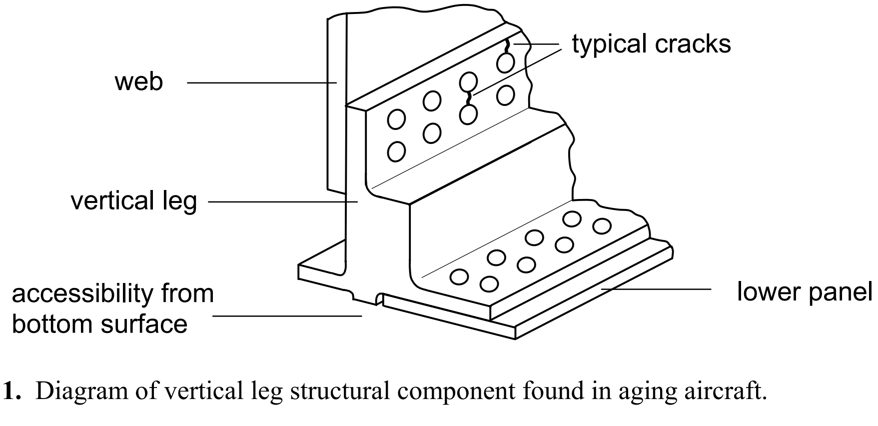

FIGURE 1. Diagram of vertical leg structural component found in aging aircraft.

investigated for improved feature classification of discontinuities in welds [5]. Multidimensional signal processing in both frequency and spatial domains has also been applied to complex signal classification problems [6]. Prior work has also investigated the analysis of adjacent signals from a moving transducer for refined crack detection around fastener holes through calculation of the variation of correlated adjacent signal [7] and the principal components of correlated adjacent signals [2]. However, features derived from amplitude and signal variation dynamics alone have not fully satisfied the classification algorithm requirements for the three case study problems.

LOCAL CORRELATION METHOD

The basic philosophy of the proposed approach is the refined use of echo dynamics by computer algorithms for improved signal characterization. To supplement the use of amplitude dynamics and signal variation dynamics for classification purposes, the use of the change in time of adjacent signals as a dynamic measure is proposed. This concept is similar the prior work on ALOK, where the amplitude and transit time dynamic curves are used for noise rejection in welds [3]. However, this methodology employs accurate time delay estimation of primary features in adjacent signals for improved secondary feature analysis. In addition, this methodology provides a general set of features for improved automated signal classification of multiple signals.

A description of the local correlation method for the estimation of the change in time dynamics is presented. The first step in the process is the selection of a set of signals of interest. Figure 2 displays a diagram of the inspection problem and a corresponding plot of a series of experimental pulse-echo signals from a moving transducer. For this problem, the signal associated with the specular reflection from the hole is defined as a primary signal that can be used for reference purposes. Signals are selected for analysis relative to a peak primary signal used for identification of the hole reference location.

The second step for this method is the alignment of adjacent signals in time using the primary signal feature. To accomplish this task, the signals are first adjusted in time based on an estimate of the wavespeed of the material, the step size between transducer locations and geometry of the hole. However, due to variation in material properties and the real step size between transducer locations, a second adjustment in the time of flight of the signals is required. This step is particularly important in order to accurately quantify the change in time dynamics for the secondary signals of interest. A variety of methods have been proposed over the years for time delay estimation of adjacent signals. A generalized correlation method for time delay estimation was presented by Knapp and Carter [8]. Methods for phase aberration correction in medical ultrasound imaging have also been studied [9-11]. Flax and O'Donnell proposed the use of cross-correlation of echoes at adjacent elements for phase aberration correction [9]. This approach was used for time delay correction of adjacent signals in this study, where a larger gate was first used for an initial time delay estimate and a second smaller gate was applied using the reference signal peak for a final time delay adjustment. With the application of this approach, the experimental pulse-echo signals of interest are consistently aligned as shown in Figure 3.

The next step performs the local analysis of the change in time dynamics for the secondary signals of interest. First, a gate in time is applied to the region of secondary signals of interest. A plot of a series of secondary signals associated with the reflected interface (creeping) wave from a far crack is shown in Figure 4. Clearly, a shift in time is observed in these secondary signals relative to the aligned primary signals. This relative shift in time is due to differences in the path geometry and wavespeed associated with these two ultrasonic signals. Figures 5(a) and 5(b) display diagrams of the rays for adjacent transducer locations corresponding to the primary specular reflection signal and the secondary reflected interface wave signals from a far crack respectively. The difference in time for the primary specular signal for adjacent sources is be given by:

$$dt_{\text{hole\_near}} = 2c_t\left[\left(\sqrt{(x_1 - x_0 - dx)^2 + (y_1 - y_0)^2} - r\right) - \left(\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} - r\right)\right] \tag{1}$$

while the difference in time for the secondary reflected interface wave signals from a far crack for adjacent sources is be given by:

$$dt_{\text{far\_crack}} = 2c_t\left[\left(\sqrt{(x_1 - x_0 - dx)^2 + (y_1 - y_0)^2 - r^2}\right) - \left(\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 - r^2}\right)\right] + 2c_{cr}\left[\alpha_{x_1+dx} - \alpha_{x_1}\right] \tag{2}$$

where c_t and c_{cr} are the wavespeeds for the shear wave and interface wave respectively. With increasing transducer distance from the hole, although the relative path length of the secondary reflected wave increases, given that path length of the interface wave on the surface of the hole is reduced with a corresponding slower wavespeed, the resulting difference in time for the secondary signal relative to the primary signal is reduced.

In order to accurately measure this observed change in time of the signals, the following algorithm was developed. First, M sets of two adjacent signals are selected. Figure 4 highlights two particular signals selected for analysis at transducer locations of x = -0.180" and x = -0.220". Second, a series of N overlapping local time gates are applied to the signals. Additional parameters for the gates include start time, gate width, and gate overlap. The use of multiple small time gates provides the capability to distinguish different signals that may be closely spaced or superimposed. Third, time delay estimation for these two signals is performed using cross correlation. Figure 4 displays this locally measured shift in time. Lastly, this process is repeated for N local gates and M adjacent signal sets forming a matrix of values associated with the change in time dynamic measure.

In the final step, feature classification can be performed by applying an acceptance criteria for the relative time shift and signal amplitude data matrices. For example, an amplitude criteria can first be used to determine what measures of change in time are significant. Subsequently, the change in time criteria can be used to differentiate between amplitude signals that are associated with signals of interest such as flaws and signals associated with part geometry. Classification algorithms can then be applied to these select amplitude signals of interest.

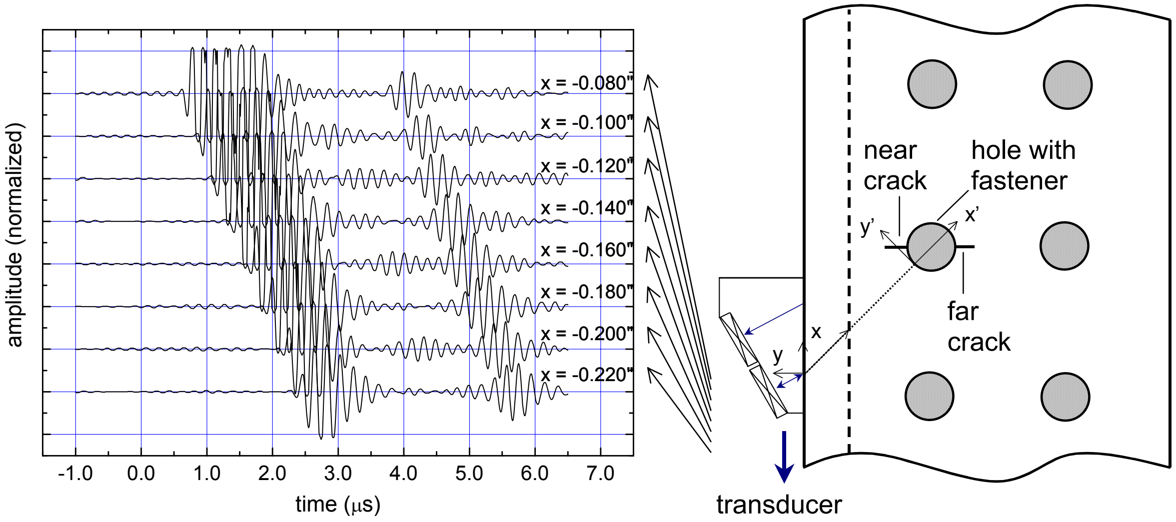

FIGURE 2. Diagram of inspection problem and associated plot of a series of experimental pulse-echo signals from a moving transducer (far crack case presented in plot.)

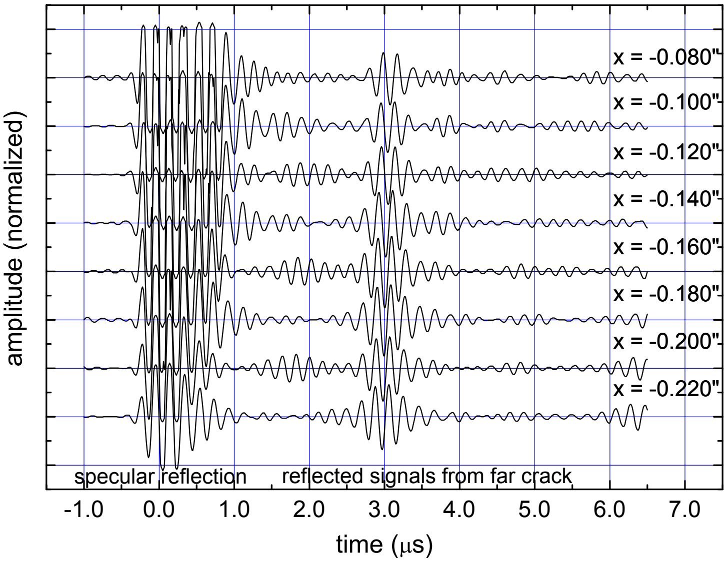

FIGURE 3. Plot of a series of signals from a moving transducer that have been aligned by the primary (specular reflection) signals using wavespeed, transducer step size, and phase aberration correction.

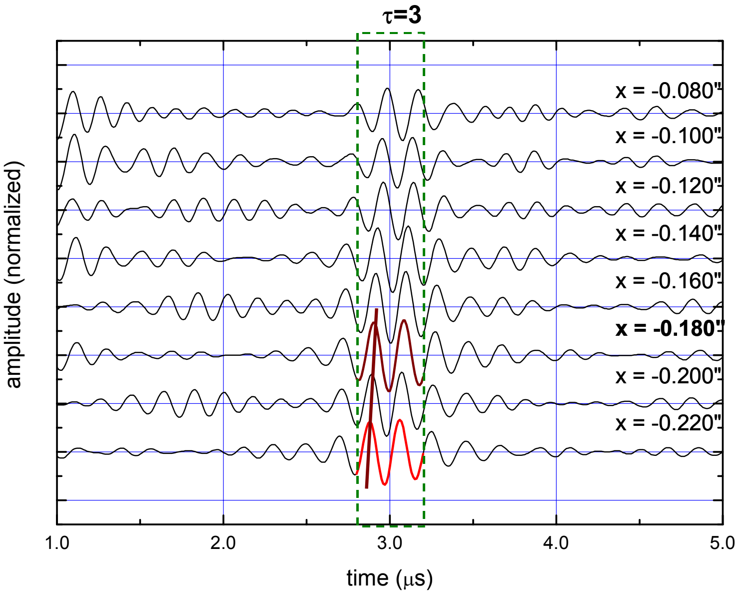

FIGURE 4. Plot of a series of signals from a moving transducer displaying the estimation of the time delay of the secondary signals using the local correlation method for a particular transducer location and time gate.

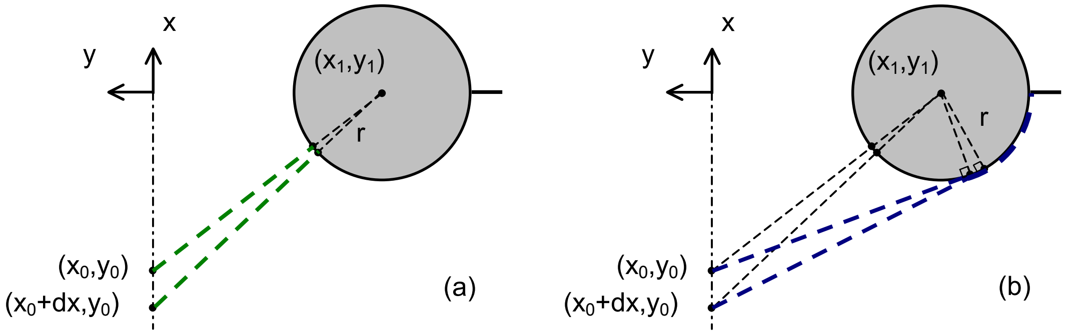

FIGURE 5. Diagram of rays for adjacent transducer locations corresponding to (a) the primary specular reflection signal and (b) the secondary reflected interface (creeping) wave signals from a far crack.

APPLICATIONS

Three applications of the local correlation method are demonstrated for the case study problem concerning holes in locations of limited accessibility that contain fasteners with sealant. These applications include the characterization of signals of multiple geometric reflectors in close proximity, signals from multiple paths, and superimposed signals.

The first application concerns the far crack detection problem shown in Figure 2. The primary objective is to detect signals associated with the reflected interface wave from a far crack. However, under certain contact conditions between the fastener and the hole, significant reradiated insert signals can be generated. These signals can occur at similar transducer locations and times of flight as the reflected crack signals, providing a difficult signal interpretation problem. A discussion including models for this problem has been previously presented [1,2]. Figures 6(a) and 6(b) present plots of a series of experimental signals from a moving transducer for the cases of reradiated insert signals and reflected interface wave signals from a far crack respectively. However, through application of the local correlation method, it is clear from these plots that the change in time dynamics of these signals can provide a means for differentiation. The lack of shift in the reradiated insert signals with a moving transducer is due to the wave path being correlated with the specular reflection path.

The second application concerns the near crack detection problem shown in Figure 2. Due to the complex vertical leg structure and depth of the hole locations relative to the transducer (Figure 1), multiple paths for the specular reflection from the hole can occur. Poor alignment of the transducer with the part is a primary source of secondary specular reflections from the hole. Given their location in time, coherent noise due to secondary specular reflection signals can interfere with the detection of the near crack tip diffraction signals. Figures 7(a) and 7(b) present plots of a series of experimental signals for the cases of secondary specular reflection from the hole and tip diffraction from a near crack respectively. Again, through application of the local correlation method, it is clearly observed from these plots that the differences in the change in time dynamics and amplitude dynamics of these signals can be used for improved signal classification.

The third application revisits the far crack detection problem where the reradiated insert signal and reflected interface wave signals from a far crack are superimposed. This condition has not been generated to date in the laboratory, but is expected to occur in the field. To study the change in time dynamics for this problem, simulated studies were performed. The 2D BEM formulation and model parameters used to generate the reradiated insert signals have been previously presented [1,2]. Results for the simulated transducer response are presented in Figures 8(a) and 8(b) for the no notch and with far notch cases respectively. Three adjacent transducer locations for each flaw condition were calculated and aligned using the primary specular signal. In Figure 8(b), the far notch case presenting the superimposed signals is easily discernable through detecting the local shift in the time signals associated with the far notch. Using the local correlation method with the application of multiple gates in time, the two signals are clearly distinguishable.

Several general statements can be made about the potential benefits of the local correlation method for flaw detection and characterization. First, the method provides the capability to distinguish between multiple reflectors due to difference in location and geometry. In addition, it can be used to reject random signals that are not locally correlated or coherent noise features that differ in amplitude and change in time dynamics relative to the signals of interest. In addition, the measurement results will not be as sensitive to changes in transducer gain or pulse shape providing greater robustness with transducer changes over time.

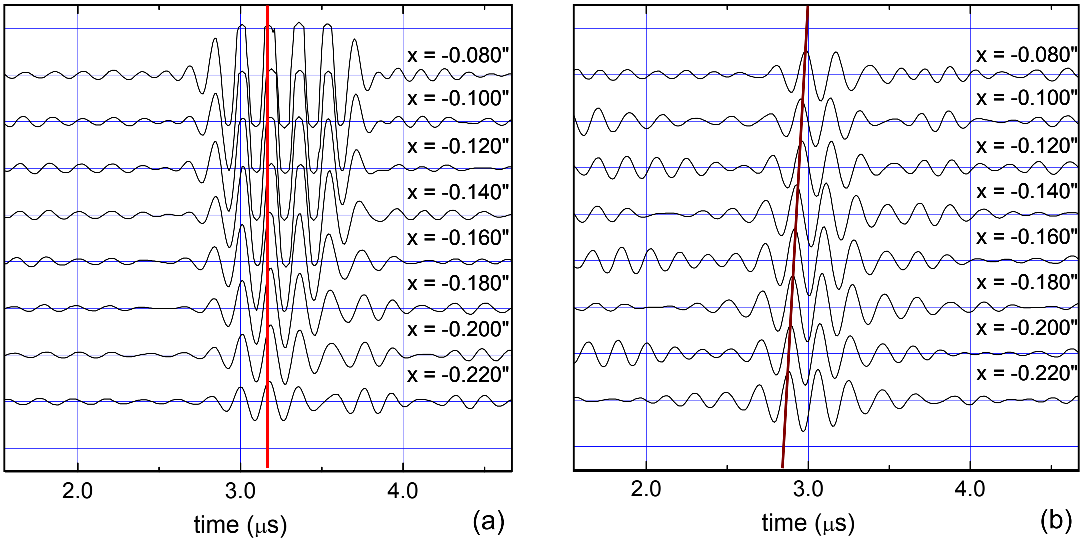

FIGURE 6. Plot of a series of signals from a moving transducer for the cases of (a) reradiated insert signals and (b) reflected interface (creeping) wave signals from a far crack.

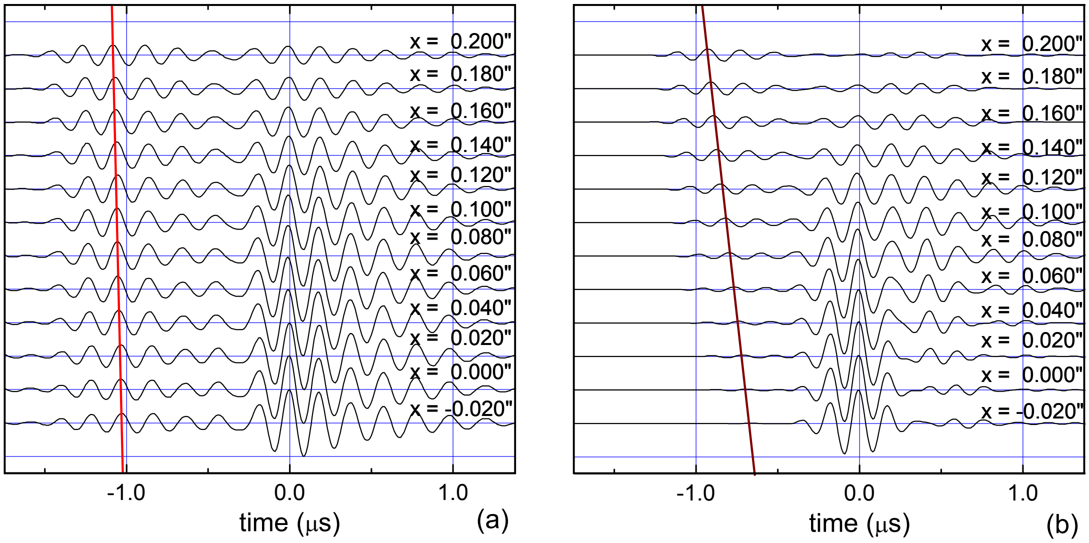

FIGURE 7. Plot of a series of signals from a moving transducer for the cases of (a) secondary specular reflection from the hole and (b) tip diffraction from a near crack (both prior to the primary specular signal.)

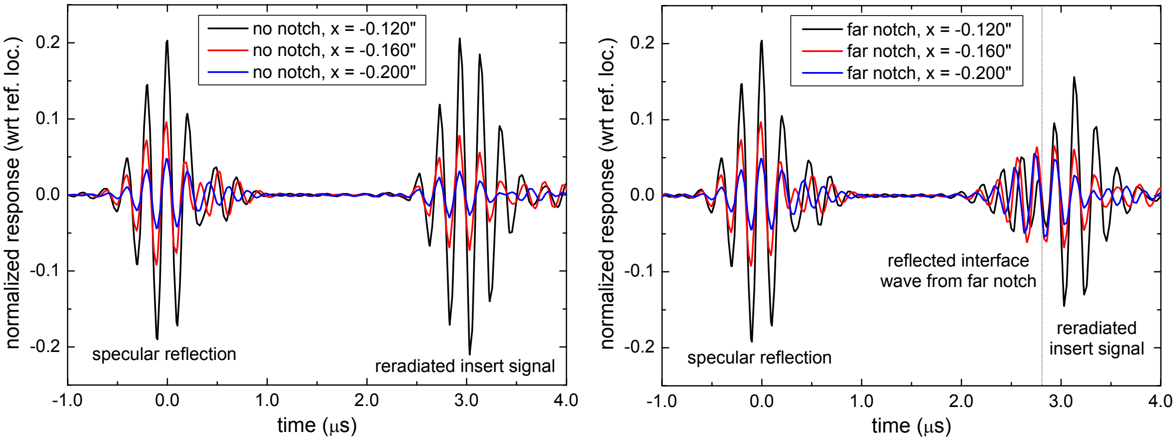

FIGURE 8. Plot of a series of simulated signals from a moving transducer for the case of a reradiated insert signal and (a) no far notch case and (b) superimposed with a far notch signal.

CONCLUSIONS AND RECOMMENDATIONS

The local correlation method was developed to detect the relative shift of signals in time for adjacent transducer locations based on the echo dynamics of the signals. The proposed approach measures the change in time of adjacent signals to supplement amplitude dynamics and signal variation dynamics for improved automated classification of multiple signals. The approach was demonstrated for a series of inspection problems in aircraft structures with limited accessibility and under in-field conditions. These applications include the characterization of signals from multiple paths, the characterization of signals from multiple geometric reflectors in close proximity, and the detection of superimposed signals. The general benefit of relative measures for NDE classification problems was also demonstrated.

Although the benefits of the local correlation method have been demonstrated for several UT NDE applications, additional work is proposed to further refine and expand its capabilities. First, alternative time delay estimation methods will be investigated for improved performance considering both fast methods and eigenstructure methods for superimposed signals. For similar feature classification problems, investigations into the use of multiple dynamic features (amplitude, change in time, signal variation) are proposed. Beyond the problem of signals from conventional ultrasonic transducers, the potential application of this concept also exists for analysis of adjacent elements in phased array transducers and multiple embedded sensors in structural health monitoring applications. The potential to compare multiple signals from embedded sensors over time may provide the capability to track crack growth with improved coherent noise rejection capability over conventional signal processing methods.

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