ADVANCED ECHO-DYNAMIC MEASURES FOR THE CHARACTERIZATION OF MULTIPLE ULTRASONIC SIGNALS IN AIRCRAFT STRUCTURES

J. Aldrin[1], C. Kropas-Hughes[2], J. Knopp[2], John Mandeville[3], David Judd[3], Eric Lindgren[3]
[1] Computational Tools, Gurnee, USA; [2] Air Force Research Laboratory, Wright-Patterson, USA;
[3] SAIC Ultra Image Int., New London, USA

Abstract: A significant challenge in nondestructive evaluation is the ability to discern signals, originating from a crack and a geometric feature in a part, that are either closely spaced or superimposed in time. An example problem is the ultrasonic inspection of aircraft holes in vertical riser structures with limited accessibility for a transducer from an external wing surface. Characteristics of the path of the ultrasonic signal and the contact condition between the fastener and hole can hinder the use of traditional amplitude dynamics for signal classification and crack detection. A local correlation method was developed to detect the relative shift of signals in time for adjacent transducer locations due to the varying echo dynamics from crack and part geometries. This approach analyzes a series of signals from a moving transducer by first accurately aligning the signals to the primary part signal feature and subsequently measuring the shifting of secondary signals of interest within multiple time windows. A methodology is proposed that supplements amplitude dynamic measures with both the change in time and signal variation measures. Feature maps of these dynamic measures are presented to demonstrate the methodology and provide a practical means for classification. Experimental and simulated studies are presented that validate this methodology for several ultrasonic NDE applications. Lastly, an alternative time delay estimation approach is presented for the local correlation method to improve computation time with comparable performance.

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 can been observed for a variety of inspection locations in aging aircraft structures since the components were not originally intended for inspection. A case study shown in Figure 1 is a vertical leg structural component.

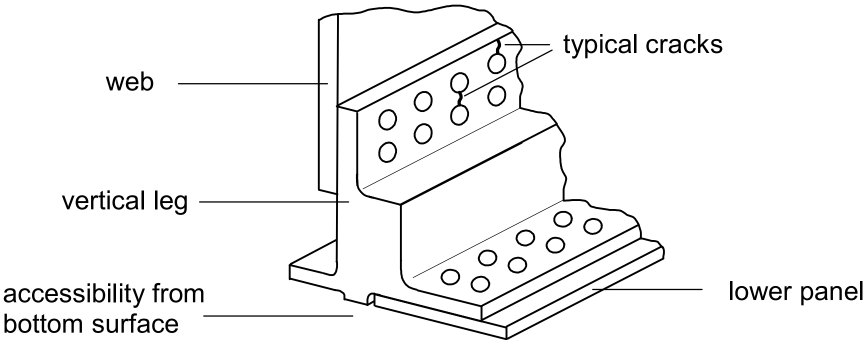


Figure 1. Diagram of a vertical leg structural component found in aging aircraft.

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 high cost for teardowns 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 for these vertical structures. For this case study, several distinct classification problems involving closely-spaced or superimposed signals can be identified. For the far crack detection problem, a creeping (interface) wave can be used to inspect the shadow region of the hole. However, for the case of holes containing fasteners with sealant and 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 creeping waves from a far crack. When considering the detection of crack on the near side of holes that are small in diameter and located deep in risers, it can be difficult to separate the specular reflection signal of the hole from the crack corner reflection signal [1].

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 [2].

To address increasingly complex data interpretation problems for inspectors in ultrasonic NDE, the application of automated signal classification (ASC) algorithms has 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 [3]. In addition to amplitude dynamics, the variation of the principal components of adjacent signals has been investigated for improved feature classification of discontinuities in welds [4]. Multidimensional signal processing in both frequency and spatial domains has been applied to complex signal classification problems [5]. 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 [6] and the principal components of correlated adjacent signals [7].

In previous work, an automated signal classification algorithm was developed and validated for this case using laboratory studies [7]. However due to the discussed signal classification issues that are present under in-field conditions, there is a need for advanced signal processing methods to generate features with greater reliability. A novel feature extraction methodology has been developed 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 [8]. This 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. This concept is similar the prior work on ALOK, where the amplitude and transit time dynamic curves are used for noise rejection in welds [2]. However, this methodology employs accurate time delay estimation of primary features in adjacent signals for improved secondary feature analysis. In addition, this new methodology provides a general set of features for improved automated signal classification of multiple signals. To more generally address such problems, a complete process is proposed that supplements amplitude dynamic measures with change in time measures and signal variation measures for robust signal classification. Feature maps of these dynamic measures are presented to demonstrate the methodology and provide a practical means for classification. Experimental and simulated examples are presented that validate this methodology for several ultrasonic NDE applications. Lastly, an alternative time delay estimation approach is presented for the local correlation method to significantly improve computation time with comparable performance.

Results: 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.

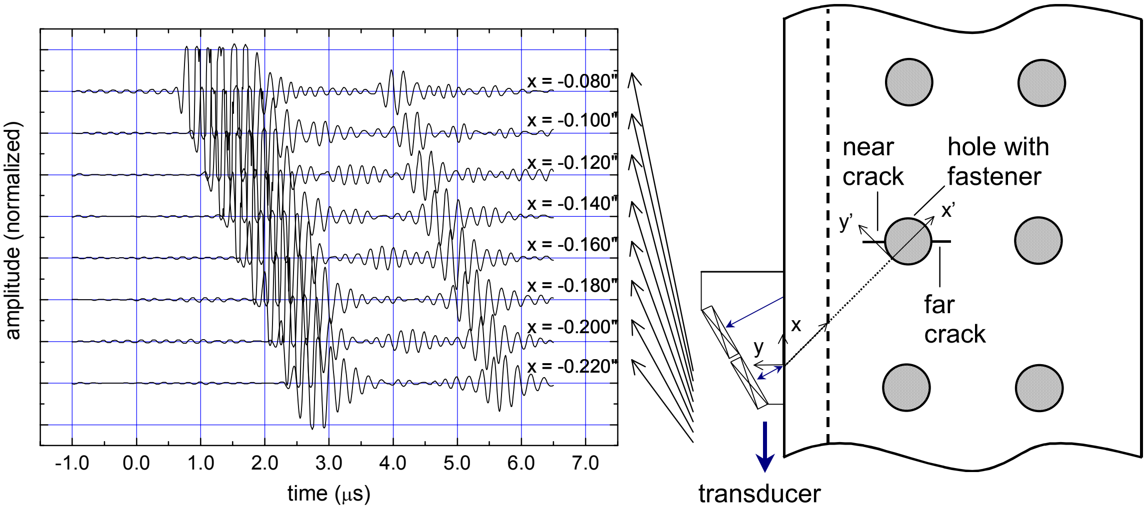
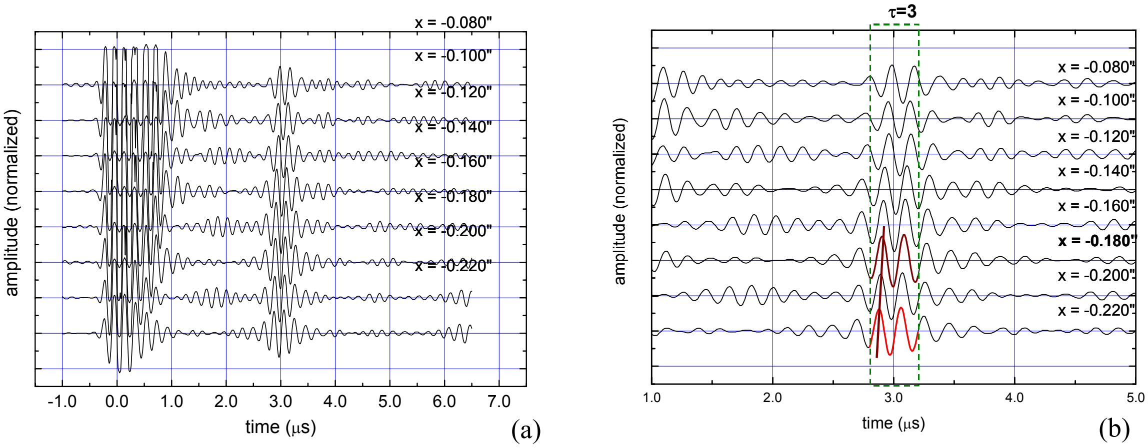


Figure 2. Diagram of inspection problem and associated plot of a series of experimental pulse-echo signals from a moving transducer (far crack case presented in plot.)

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 [9]. Methods for phase aberration correction in medical ultrasound imaging have also been studied [10-11]. Flax and O'Donnell proposed the use of cross-correlation of echoes at adjacent elements for phase aberration correction [11]. 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(a).



(a) (b)

Figure 3. Plot of a series of signals from a moving transducer (a) after aligning by the primary signals and
(b) displaying the estimation of the time delay of the secondary signals using the local correlation method.

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 3(b). 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 4(a) and 4(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.

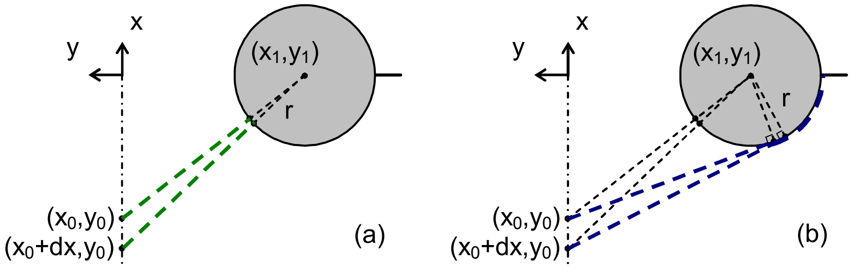


Figure 4. Diagram of rays for adjacent transducer locations corresponding to (a) the primary specular reflection signal and (b) the secondary reflected interface (creeping) wave signals from a far crack.

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 3(b) 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 3(b) displays this locally measured shift in time. This process is then repeated for N local gates and M adjacent signal sets forming a matrix of values associated with the change in time dynamic measure.

Lastly, 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. Feature maps of these dynamic measures are also presented as a practical means for classification. For some complex classification problems, the use of change in time and signal variation measures to supplement amplitude dynamic measures are explored. Applications of this methodology are presented in the next section.

Discussion: 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. Figures 5(a) and 6(a) present plots of a series of experimental signals from a moving transducer for the cases of reflected interface wave signals from a far crack and reradiated insert signals respectively.

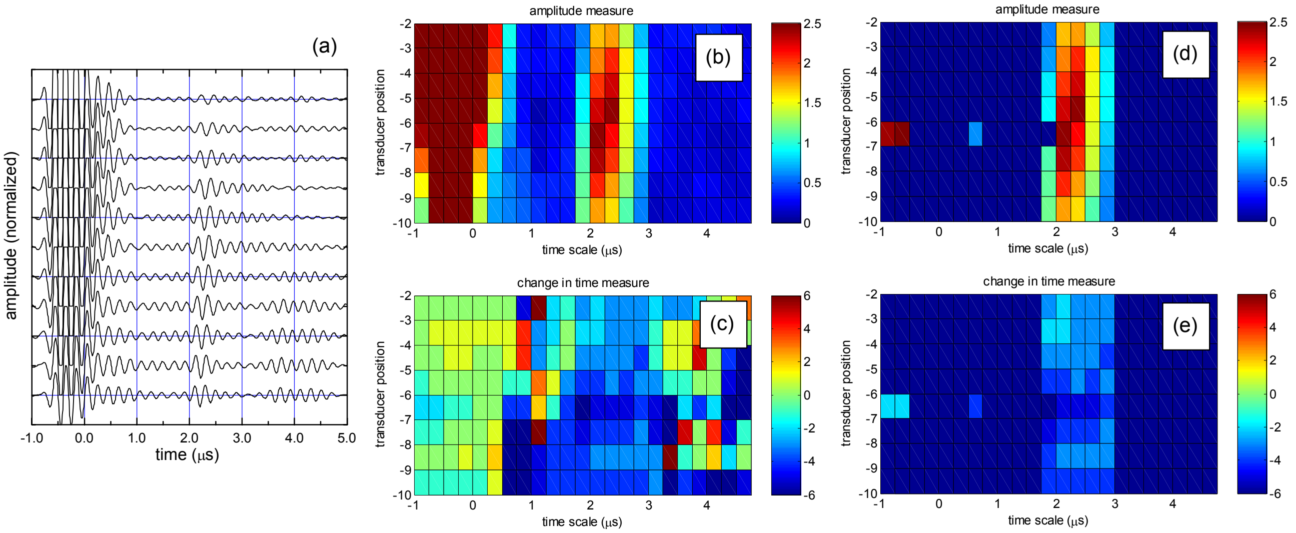


Figure 5. Plot (a) of a series of signals from a moving transducer for the far crack case with associated feature maps of (b) amplitude measure, (c) change in time measure, (d) filtered amplitude measure for far crack detection and (e) filtered change in time measure for far crack detection.

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. To enhance the data for classification purposes, feature maps are presented in Figures 5(b), 5(c), 6(b), and 6(c) for the amplitude and change in time dynamic measures for the two case conditions. With the application of minimum amplitude thresholds and change in time gates settings, corresponding filtered feature map shown in Figures 5(d), 5(e), 6(d), and 6(e) provide clear features for differentiating the crack and no crack cases.

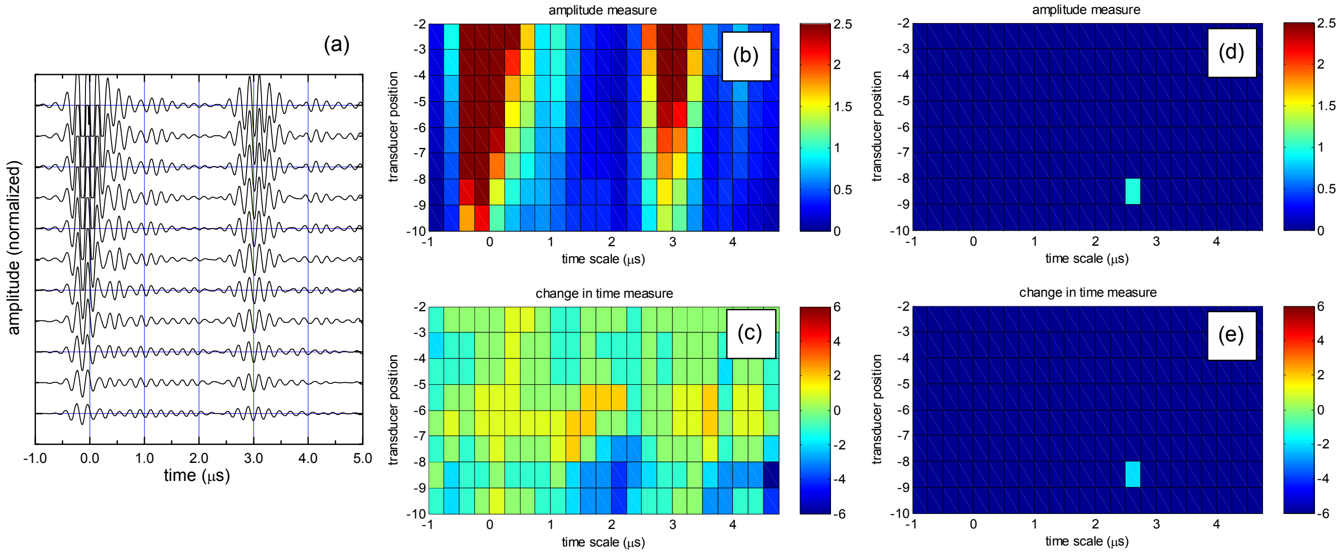


Figure 6. Plot (a) of a series of signals from a moving transducer for the no far crack and with reradiated insert signal case with associated feature maps of (b) amplitude measure, (c) change in time measure, (d) filtered amplitude measure for far crack detection and (e) filtered change in time measure for far crack detection.

Next, the far crack detection problem is considered where reradiated insert signals and reflected interface wave signals from a far crack are superimposed. To study the change in time dynamics for this problem, simulated studies were initially performed. The 2D BEM model and parameters used to generate reradiated insert signals have been previously presented [1,8]. Results for the simulated transducer response are presented in Figures 7(a) and 7(b) for the no notch and with far notch cases respectively. In Figure 7(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. Figure 8 presents experimental data for this case where both reradiated insert signals and reflected interface wave signals from a far crack are present. Clearly, with the use of feature maps for the amplitude and change in time measures in conjunction with minimum amplitude thresholds and change in time gate settings, it is feasible to generate feature maps that classify crack signals in light of insert signals.

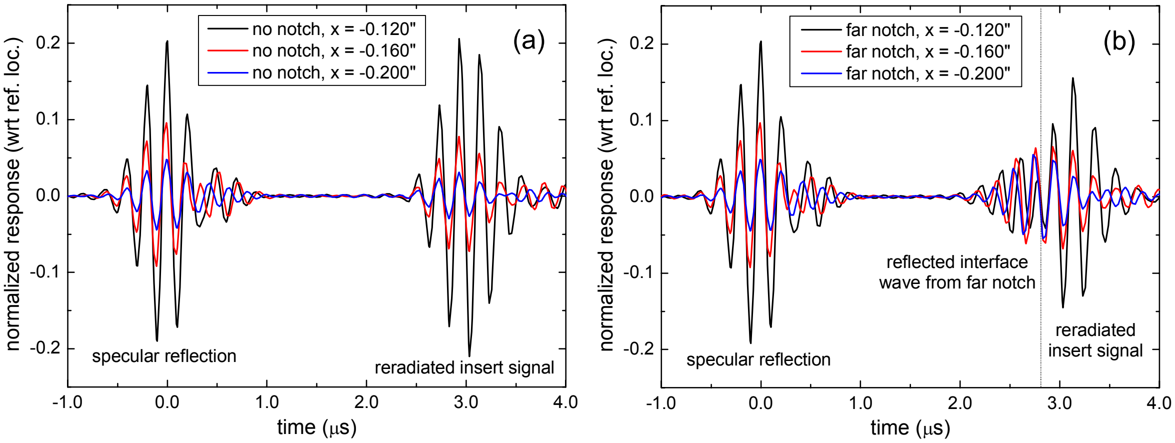


Figure 7. Plot of a series of signals from a moving transducer for the cases of (a) reradiated insert signals and (b) reflected interface (creeping) wave signals from a far crack.

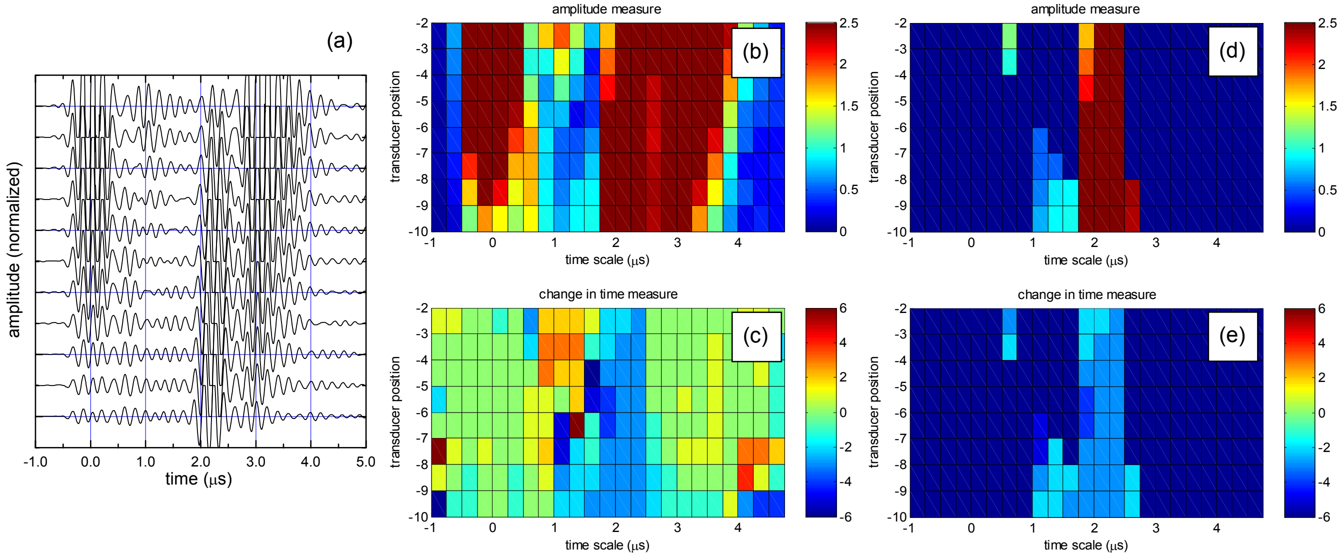


Figure 8. Plot (a) of a series of signals from a moving transducer for the with far crack and with reradiated insert signal case with associated feature maps of (b) amplitude measure, (c) change in time measure, (d) filtered amplitude measure for far crack detection and (e) filtered change in time measure for far crack detection.

A final example concerns the near crack detection problem shown in Figure 2. When considering the detection of cracks on the near side of holes that are small in diameter and located deep in risers, it can be difficult to separate the specular reflection signal of the hole from the crack corner reflection signal. However, subtle changes in amplitude, change in time of flight, and signal variance as a transducer is moved past a hole can be used for classification purposes. An example is presented in Figure 9 of series of signals from a moving transducer for a near crack case with associated amplitude, change in time, and signal variation feature maps.

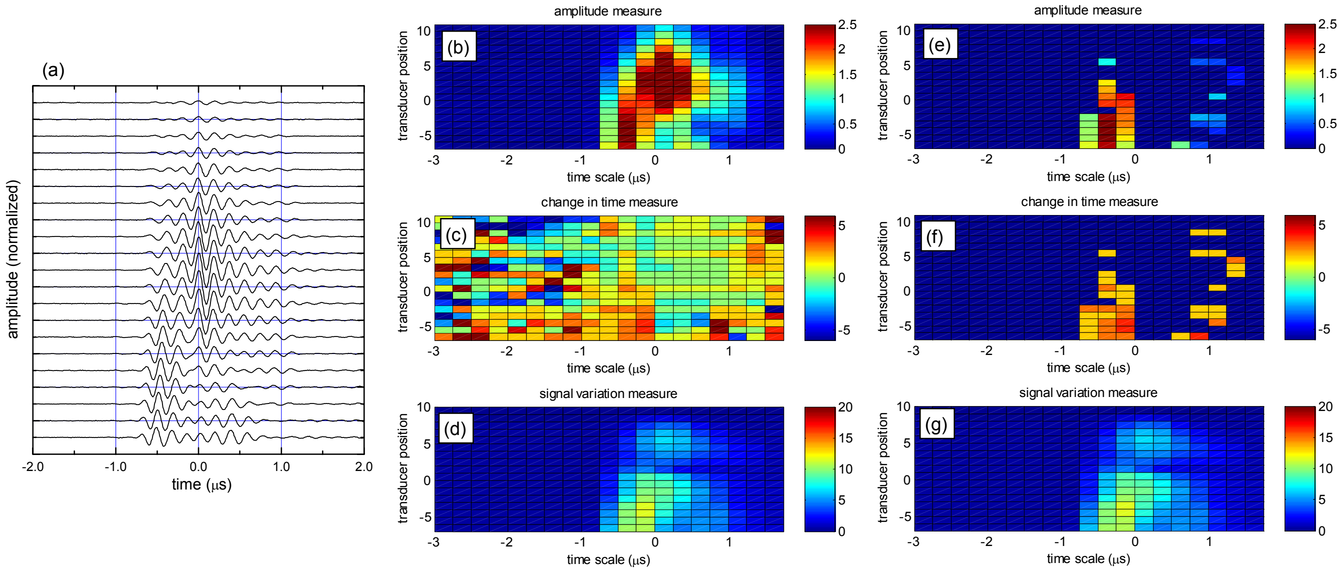


Figure 9. Plot (a) of a series of signals from a moving transducer for a near crack case with associated feature maps of (b) amplitude measure, (c) change in time measure, (d,g) signal variance measure, (e) filtered amplitude measure for far crack detection, (f) filtered change in time measure for far crack detection.

Using the local correlation method to align the primary signal associated with specular reflection from the hole, strong secondary features associated with a near crack can be quantified using the change in time and signal variation measures. Again, advanced echo dynamic measures presented in filtered feature maps demonstrate the ability to isolate crack signals in the presence of coherent signals associated with the part geometry.

Lastly, an alternative time delay estimation approach was considered for the local correlation method to improve computation time while maintaining comparable performance. In order to address the high computational cost of cross correlation calculations, Karaman et al. presented a phase aberration correction method based on the minimization of the sum of the absolute difference between two signals [11]. Fundamentally, multiplication operations are replaced by subtraction operations resulting in a reduction in overall computation time. The sum of the absolute difference technique was incorporated into the local correlation method and the impact on change in time calculations were investigated using several example cases. In general, the sum of the absolute difference technique was found to provide similar calculations within acceptable accuracy variation for the change in time calculation between two adjacent signals. In addition, since the difference-based approach is less sensitive to the maximum portions of the signal with respect to cross correlation calculation, more accurate calculations are possible when saturation of the signal peaks occurs. However to fully validate the sum of the absolute difference technique, an exhaustive study is proposed incorporating an array of significant signal variation and noise signals parameters.

Conclusions: Several general statements can be made about the benefits of advanced echo dynamic features for flaw detection and characterization. First, the method provides the capability to distinguish between multiple reflectors due to differences 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 from the echo dynamic measures of the signals of interest. In addition, given the use of relative measures, the classification results will not be as sensitive to changes in transducer gain or pulse shape providing greater robustness with transducer changes over time.

Lastly, the use of feature maps with basic filters and simple decision trees can provide robust data classification schemes for a variety of applications in ultrasonic NDE.

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. Alternative time delay estimation techniques will be investigated using eigenstructure methods for characterizing superimposed signals. The potential application of this concept also exists for the 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.

Funding was provided by the Air Force Office of Scientific Research through AFRL/MLLP, Wright Patterson AFB OH. Support was provide by SAIC Ultra Image Int. in the construction of experimental samples through funding from Warner Robins ALC.

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