Detection of Structural Damage from the Local Temporal Coherence of Diffuse Ultrasonic Signals

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Abstract—Permanently mounted ultrasonic transducers have the potential to interrogate large areas of a structure, and thus be effective global sensors for structural health monitoring. Recorded signals, although very sensitive to damage, are long, complex, and difficult to interpret compared to pulse echo and through transmission signals customary for nondestructive testing. These diffuse signals also are quite sensitive to environmental effects such as temperature and surface condition changes. Waveform comparison methods such as time domain differencing and spectral analysis, although effective for detecting changes, are generally unsuccessful in discriminating damage from environmental effects. This paper considers the local temporal coherence as another means of comparing two waveforms in order to provide a quantitative measure of the change in shape of a signal compared to a reference as a function of time from transmit. Experimental results show that the local temporal coherence is effective in discriminating structural damage from both temperature changes and modest changes in surface conditions; results are compared to those obtained from time domain and spectrogram differencing. The advantages of this methodology are the simplicity of the transducers, the applicability to a wide range of structures, and the straightforward signal processing.

I. INTRODUCTION

There is an ever-increasing expectation for safer and more reliable structures as technology advances and infrastructure ages. Current inspection practices are time consuming and often require taking the structure out of service. The goal of a system for structural health monitoring (SHM) is to detect defects and predefect material changes, reducing or eliminating the need for scheduled inspections while simultaneously providing an increased level of reliability.

Many proposed sensors for monitoring the health of a structure are capable only of local measurements of parameters such as temperature, displacement, or strain. In contrast, ultrasonic transducers generate elastic waves that propagate long distances and thus have the potential to obtain information about the entire material volume through which the wave has propagated. Because ultrasonic waves are high frequency elastic vibrations of the material itself, they are directly affected by geometry, microstructure, and any damage that may be present.

The approach taken for most ultrasonic nondestructive evaluation (NDE) methods is to either move a single transducer over a large area (either manually or with an automated system), or use a large number of transducers (either an array or many discrete transducers) in order to cover the required region for inspection; neither of these approaches is suitable for an in situ SHM system. The preferred scenario for an ultrasonic SHM system is to mount a small number of sensors permanently on, in, or near the structure, and either continuously or intermittently activate them in order to monitor the ultrasonic response. Much research has concentrated on this general approach based upon either generating single mode guided waves (i.e., Rayleigh or Lamb waves) that can travel long distances with little dispersion and are relatively simple to analyze [1], [2], or decomposing a multimode guided wave signal into identifiable modes for analysis [3]. These methods are limited to structures that support guided waves (e.g., plate-like structures), and typically have problems dealing with reflections from boundaries.

An alternative approach is to excite an ultrasonic source and measure the resultant long-time, or diffuse, wave field. A diffuse wave field is one in which the energy is randomly diffused throughout the structure and can be associated with a strongly scattering medium or one in which there are very large numbers of internal reflections. A practical definition of a diffuse wave field is one in which it is not possible to identify features in the recorded ultrasonic signal as being from specific bulk or guided wave mode arrivals. The recorded diffuse wave often is preceded by clearly identifiable ballistic (or coherent) echoes from longitudinal, shear, and surface waves. Diffuse-like waves are the basis for the NDE acousto-ultrasonic (AU) method whereby an active ultrasonic transducer is the source, a passive ultrasonic transducer is the receiver, and signals are recorded until they have decayed to insignificant amplitudes. Thus, the AU method combines the active source of ultrasonic testing with the long duration and complex signals of acoustic emission testing. This method has had limited, practical success because the received signals are very complex, signal features do not always correlate to the material properties of interest, and the signals are very sensitive to transducer and specimen mounting variations.

Although there is widespread agreement that diffuse signals are very sensitive to material changes, it is a chal-

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lenging problem to reliably and quantitatively correlate the ultrasonic response to actual structural conditions, particularly in the face of variations in transducers and coupling combined with environmental effects and changes in specimen boundary conditions. But the permanently mounted ultrasonic sensors of an SHM system offer the significant advantage of eliminating the lack of repeatability of transducers and coupling conditions, which makes practical the application of differential time-domain analysis methods. In this paper, the local temporal coherence between a measured signal and a reference signal recorded on an undamaged structure is investigated as a tool for damage detection. A methodology is presented for analyzing the recorded signals, and data are reported from aluminum specimens subjected to both environmental and structural changes. For comparison, time-domain and spectrogram differencing methods also are implemented, and results are compared to those obtained from the local temporal coherence.

II. BACKGROUND

Diffuse wave field theory was first considered for elastic wave propagation in the early 1980s [4], and early experimental work by Weaver [5] investigated the dependence of the estimated power spectra on source type and location. Until recently, most theory and experiments with diffuse ultrasonic waves have taken the basic approach of estimating time-varying spectral content in some fashion and have not been concerned with either modeling or analyzing the details of the time domain waveforms. However, that is changing in some small degree as Weaver and Lobkis [6] have shown that complex waveforms recorded from a diffuse field undergo almost a pure dilation when subjected to a temperature change. Lobkis and Weaver [7] also have shown that long-time cross correlations between two signals recorded from a diffuse wave field at separate locations can, under optimum experimental conditions, be used to recover the corresponding Green’s function of the specimen. Michaels and Michaels [8] showed that simple, time-domain differencing combined with accumulating energy is effective for monitoring damage under controlled laboratory conditions. Michaels et al. [9] demonstrated that a combination of differential features from both the time and frequency domains can be used to discriminate damage from environmental changes.

The AU technique, which is essentially generation and analysis of diffuse ultrasonic signals, was first developed in the late 1970s as an NDE tool for inspecting composite materials [10], [11]. Due to the complexity of the signals, they were analyzed using empirical methods similar to those used for acoustic emission testing. Kiernan and Duke [12] further developed methods for analyzing AU signals by calculating moments of the power spectrum and functions of those moments, which they called AU parameters. Guo and Cawley [13] related AU signal characteristics to those of Lamb waves for plate specimens and noted the sensitivity of the method on geometry, coupling, and instrumentation settings. Mazzeranghi and Vangi [14] investigated several methods for analyzing diffuse ultrasonic signals, including time-domain waveform differencing, in an attempt to minimize temperature effects; results were promising but methods were specimen specific and required monitoring of temperature. Gyekenyesi et al. [15] combined diffuse wave theory with the AU parameter approach by additionally computing diffuse field decay rates. They concluded that the total energy and the diffuse field decay rate correlate well to damage in a composite specimen, but that these parameters are strongly influenced by transducer coupling conditions and the specimen support structure.

Although the AU technique has been the subject of considerable research, there has been no comprehensive theoretical treatment and inconsistent evidence of its efficacy under realistic testing conditions [16]. Consequently, it has not received widespread commercial acceptance. It is typically applied to structures with distributed damage because this type of damage is expected to most influence diffuse field decay rates. The limiting factor in use of the method is an effective methodology for analyzing the received signals as there is widespread agreement and much experimental evidence that the signals contain useful information regarding the internal structure of the material being tested. A comparison of research results on diffuse ultrasonic wave theory and the AU method indicates common conclusions: signals recorded from an elastic wave field composed of many reflections, either from scatterers or from boundaries, are very sensitive to subtle changes in the medium of propagation, the source, and the receiver; and estimating time-dependent power spectra and calculating shape parameters is one useful way to quantify diffuse ultrasonic signals. These conclusions suggest that diffuse ultrasonic waves can be applied to structural health monitoring with permanently mounted sensors in which changes in the diffuse wave field are correlated to damage, although only a few applications have been reported in the literature [8], [14], [17].

III. ANALYSIS METHODOLOGY

Three analysis methods are implemented for quantitatively comparing two diffuse ultrasonic signals: time-domain differencing, spectrogram differencing, and local temporal coherence. For all three methods, parameters are computed that are a measure of the difference between the two signals, and the efficacy of these parameters in discriminating damage from environmental changes is evaluated. In particular, consider a reference signal \( x_r(t) \) and a measured signal \( x_m(t) \) in the time domain, both of fixed length \( T \). For a sampling frequency \( f_s \), the sampled signals are \( x_r(n) \) and \( x_m(n) \) where \( n \) corresponds to the sample at time \( n/f_s \) and the length is \( N = f_sT \). The three methods all address comparison of the measured signal to the reference.

\[ x_r(n), x_m(n) \]
A. Time Domain Differencing

A straightforward way to compare these signals in the time domain is simple subtraction:

\[ d(n) = x_m(n) - x_r(n). \]  

To be most useful, the difference signal \( d(n) \) should be independent of the amplitude of the original signals. Thus, the measured and reference signals are scaled in the following manner:

\[
\tilde{x}_m(n) = \frac{x_m(n)}{\sqrt{\sum_{n=0}^{N-1} x^2_m(n)}},
\]

\[
\alpha = \frac{\sum_{n=0}^{N-1} \tilde{x}_m(n)x_r(n)}{\sum_{n=0}^{N-1} x^2_r(n)},
\]

\[
\tilde{d}(n) = \tilde{x}_m(n) - \alpha \cdot x_r(n).
\]

Note that the measured signal is scaled to unity energy, and \( \alpha \), the scale factor of the reference signal, is calculated to minimize the mean squared error between \( \tilde{x}_m(n) \), the unity energy measured signal, and the scaled reference signal. Thus \( \tilde{d}(n) \) is an amplitude-independent measure of the difference between the signals. The energy of \( \tilde{d}(n) \) within a specified time window, referred to here as the temporal residual energy, is calculated as a measure of this difference by:

\[
E = \sum_{n=n_1}^{n_2} \tilde{d}^2(n),
\]

where \( n_1 \) and \( n_2 \) are the start and stop indices corresponding to the selected time window.

B. Spectrogram Differencing

Because diffuse ultrasonic signals are nonstationary, a time-frequency representation is a logical choice for investigating differences between two such signals. The spectrogram is computed from the short-time Fourier transform (STFT), where the STFT of a discrete time signal \( x(n) \) of length \( N \) is defined as [18]:

\[
X(n, k) = \sum_{m=0}^{N-1} x(m)w(m - n)e^{-j\frac{2\pi km}{M}},
\]

where \( w(n) \) is a window function of length \( M < N \), and the frequency index \( k \) (\( 0 \leq k < M \)) is related to the continuous frequency \( f \) by:

\[
f = \frac{k}{M} f_s.
\]

Typically \( X(n, k) \) is not computed for every value of \( n \), but a decimation factor \( L \) is specified and \( X(n, k) \) is obtained for every \( L \)th value of \( n \) (i.e., \( n = 0, L, 2L, \ldots \)):

\[
X(n, k) = \sum_{m=0}^{N-1} x(m)w(m - nL)e^{-j\frac{2\pi km}{M}},
\]

where \( n \) is now related to continuous time \( t \) by:

\[
t = \frac{nL}{f_s}.
\]

The spectrogram is the magnitude of the complex STFT, \(|X(n, k)|\).

In a similar manner as for time-domain differencing, the spectrogram of the reference signal, \( X_r(n, k) \), can be subtracted from that of the measured signal, \( X_m(n, k) \), over a specified time interval and frequency window. This subtraction is performed after normalization, and two normalization methods are used. For the first method, both spectrograms are globally normalized to unity energy within the window of interest before differencing, and \( D(n, k) \) is the difference between the normalized spectrograms:

\[
D(n, k) = \frac{|X_m(n, k)|}{\sqrt{\sum_{\hat{n}=n_1}^{n_2} \sum_{\hat{k}=k_1}^{k_2} X_m(\hat{n}, \hat{k})X_m^*(\hat{n}, \hat{k})}} - \frac{|X_r(n, k)|}{\sqrt{\sum_{\hat{n}=n_1}^{n_2} \sum_{\hat{k}=k_1}^{k_2} X_r(\hat{n}, \hat{k})X_r^*(\hat{n}, \hat{k})}}.
\]

The energy of the difference, referred to here as the spectral residual energy, is calculated as:

\[
E = \sum_{n=n_1}^{n_2} \sum_{k=k_1}^{k_2} D^2(n, k).
\]

For the second normalization method, the spectrogram at each time index \( n \) is first normalized to unity energy over the specified frequency range prior to differencing in order to obtain a time-normalized spectrogram, and the difference then is calculated as:

\[
D(n, k) = \frac{|X_m(n, k)|}{\sqrt{\sum_{k=k_1}^{k_2} X_m(n, \hat{k})X_m^*(n, \hat{k})}} - \frac{|X_r(n, k)|}{\sqrt{\sum_{k=k_1}^{k_2} X_r(n, \hat{k})X_r^*(n, \hat{k})}}.
\]

The energy of the difference, referred to here as the time-normalized residual energy, is calculated as per (11).
amplitude, earlier time, portions of the signal dominate the residual energy. The second method normalizes the energy as a function of time, and thus the residual energy is an averaged local measure of how the spectral content is changing with time in which all time windows are equally weighted irrespective of absolute signal amplitudes.

C. Local Temporal Coherence

The local, or short-time, temporal coherence is a measure of the time-dependent, shape change between two signals. The term local temporal coherence is used both to emphasize the local nature of the coherence in the time domain and to distinguish it from the spectral coherence function [19]. Note that the spectral coherence function is not the Fourier transform of the temporal coherence.

The local temporal coherence is based upon the cross correlation $R_{12}(t, \tau)$ between two time invariant signals $x_1(t)$ and $x_2(t)$, which is defined as [20]:

$$R_{12}(t) = \mathbb{E}[x_1(t)x_2(t + \tau)],$$  \hspace{1cm} (13)

where $\mathbb{E}$ denotes expectation. The time of the cross-correlation peak typically is used to estimate the time delay between the two signals if they are sufficiently similar in shape.

The normalized cross correlation, or temporal coherence, provides an amplitude-independent measure of the similarity in shape of the two signals when the second signal is delayed by $\tau$ from the first:

$$\gamma_{12}(\tau) = \frac{R_{12}(\tau)}{\sqrt{R_{11}(0)R_{22}(0)}}.$$  \hspace{1cm} (14)

For signals of length $T$ centered at time $t = 0$, the cross correlation and coherence are estimated by:

$$\hat{R}_{12}(\tau) = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x_1(s)x_2(s + \tau)ds,$$  \hspace{1cm} (15)

$$\hat{\gamma}_{12}(\tau) = \frac{\hat{R}_{12}(\tau)}{\sqrt{\hat{R}_{11}(0)\hat{R}_{22}(0)}}.$$  \hspace{1cm} (16)

For time-varying processes, a local, or short-time, cross correlation is estimated within a window of length $T$ and at a particular time $t$ by:

$$\hat{R}_{12}^T(\tau, t) = \frac{1}{T} \int_{t-\frac{T}{2}}^{t+\frac{T}{2}} x_1(s)w(s-t)x_2(s + \tau)w(s + \tau - t)ds,$$  \hspace{1cm} (17)

where the windowing function $w(t)$ is typically rectangular. The corresponding estimate of local coherence at time $t$, also called the time-windowed correlation coefficient function or normalized cross correlation, is:

$$\hat{\gamma}_{12}^T(\tau, t) = \frac{\hat{R}_{12}^T(\tau, t)}{\sqrt{\hat{R}_{11}^T(0, t)\hat{R}_{22}^T(0, t)}}.$$  \hspace{1cm} (18)

Note that the maximum possible magnitude of $\hat{\gamma}_{12}^T(\tau, t)$ is unity, which is the case only when $x_1(t)$ and $x_2(t)$ have identical shape within the window centered at time $t$.

There are many examples in the literature of estimating time delay from the local coherence. Omologo and Svaizer [21] used the local coherence between acoustic events recorded with two spatially separated microphones in order to estimate the position of the acoustic source. Similarly, Thorne and Holdaway [22] apply the local coherence for measuring current velocities from acoustic signals backscattered from suspended particles in moving fluids. In biomedical ultrasonic strain imaging (elastography), the depth-dependent strain resulting from an applied displacement is measured from the local coherence between ultrasonic waveforms recorded before and after the displacement [23], [24]. Weaver and Lobkis [6] use a local cross correlation to obtain time-dependent time shifts between two ultrasonic signals caused by temperature changes. In all of these cases, the lag of the local coherence (or local cross correlation) is a mechanism to estimate time-dependent time delays between two signals.

There are several instances in the literature of quantitatively considering the magnitude of the local temporal coherence. Snieder et al. [25] and Snieder [26] relate the loss in coherence to the average displacement of scatterers for multiply scattered seismic waves. Lobkis and Weaver [27] define distortion as the logarithm of the peak of the local coherence and show that, for a temperature change, distortion is proportional to both time and volume-to-surface ratio, and quadratic with both the temperature difference and frequency.

For the work presented here, two useful curves are defined that are calculated from the local coherence $\hat{\gamma}_{12}^T(\tau, t)$. These curves are $C_{12}(t)$, the peak coherence as a function of time, and $D_{12}(t)$, the delay as a function of time:

$$C_{12}(t) = \max_\tau |\hat{\gamma}_{12}^T(\tau, t)|,$$  \hspace{1cm} (19)

$$D_{12}(t) = \arg\max_\tau |\hat{\gamma}_{12}^T(\tau, t)|.$$  \hspace{1cm} (20)

Peak coherence is the peak of the absolute value of $\hat{\gamma}_{12}^T(\tau, t)$ with respect to $\tau$ at each time $t$, and delay is the cross-correlation lag $\tau$ of the peak of the local coherence at time $t$.

As an illustration, these curves are calculated for a diffuse ultrasonic signal $x_1(t)$ and a second signal $x_2(t)$ that is synthetically derived from the first signal. Both signals are shown in Fig. 1. Note that $x_2(t)$ has been created from $x_1(t)$ by stretching $x_1(t)$ from 210 to 610 $\mu$s, applying attenuation and adding noise. Attenuation was applied in the form of a weighting function that was unity from 0 through 612 $\mu$s, and linearly decreased to a constant value of 0.2 at 1000 $\mu$s. The additive noise signal was constructed by creating a zero mean white noise time series with a standard deviation equal to 5% of the peak signal amplitude, then filtering it between 100 kHz and 1 MHz to approximately match the bandwidth of the signal. Fig. 2 shows the envelope of the coherence between the two signals as...
determined from the magnitude of the analytic signal at each value of time \( t \), in which the imaginary part of the analytic signal is the Hilbert transform of \( \hat{\gamma}_{12}(\tau, t) \) with respect to \( \tau \) at time \( t \) \[28\]. The time window \( T \) is 100 \( \mu s \), and the time increment is 20 \( \mu s \). The central ridge at a lag of approximately zero \( \mu s \) corresponds to the peak of the cross correlation and would be exactly unity for the case of identical signals. The width of this ridge is inversely proportional to the bandwidth of the signals. Broadband signals result in a sharper cross-correlation peak and thus a narrower ridge. The two orthogonal ridges at approximately 525 and 750 \( \mu s \) are in essence very broad cross-correlation peaks that correspond to locally narrowband signals.

Fig. 3 shows peak coherence and delay curves, both as a function of time. The entire local coherence map, as well as the derived peak coherence and delay, contains information concerning how one signal changes with respect to the other as a function of time. The peak coherence is a measure of the shape change, and the delay is a measure of the local time shift. From the peak coherence plot of Fig. 3(a), it can be seen that the two signals are coherent for early times but lose coherence as the second signal is attenuated and the signal-to-noise ratio (SNR) decreases.

Referring to Fig. 3(b), the delay starts at zero and linearly increases between 210 to 610 \( \mu s \) as the second signal is stretched relative to the first. The outliers in the delay curve after 800 \( \mu s \) are due to the signals no longer being coherent, corresponding to small values of peak coherence.

Parameters are calculated from the peak coherence and delay curves to capture significant aspects of their behavior. An indicator of the change in peak coherence as a function of time is the difference between its maximum and average values; this parameter is designated as \( P_1 \):

\[
P_1 = \max[C_{12}(t)] - \overline{C}_{12}. \tag{21}\]

A measure of the overall stretching or contracting of the signal relative to the reference is obtained by fitting the time delay \( D_{12}(t) \) to a straight line. Only values are used for which the peak coherence is large (typically \( > 0.6 \)); the slope of this line is designated as \( P_2 \):

\[
\hat{D}_{12}(t) = D_0 + P_2 t. \tag{22}\]

Thus, the first parameter, \( P_1 \), is a measure of how much the coherence peak has dropped relative to its maximum value, and the second parameter, \( P_2 \), is a measure of the overall stretching (or contracting) of the signal.
IV. Experimental Setup and Measurements

Measurements were made on three different 6061 aluminum plates as summarized in Table I and illustrated in Fig. 4. These specimens, although simple in both material and geometry, are of interest because reflections from the boundaries play a major role in the recorded signals, and the geometry is not suitable for propagation of guided waves over long distances. The transducers were constructed with longitudinally polarized, 2.25 MHz PZT disks, 12.5 mm diameter, and were attached to the specimen using cyanoacrylate adhesive. A conventional ultrasonic pulser receiver (Panametrics 5072PR, Panametrics NDT, Waltham, MA) was used for spike mode transducer excitation and waveform amplification. Waveforms were digitized with a sampling rate of 12.5 MHz and a resolution of 8 bits, and each recorded waveform was the average of 50 signals. There were two transducers attached to specimens #1 and #2, and thus a single through transmission signal was recorded for each measurement. Specimen #3 used four transducers, resulting in six unique source-receiver pairs (1 → 2, 1 → 3, 1 → 4, 2 → 3, 2 → 4, and 3 → 4). These six signals were recorded for each measurement. For all measurements, the specimens were supported by rubber spacers so that surface conditions could be controlled.

The specimens were first subjected to environmental conditions consisting of both temperature changes and varying surface conditions as summarized in Table I. Surface conditions were changed by both wetting the specimen (surface moisture and partial immersion), and by placing objects (e.g., metal blocks) on the top surface that were acoustically coupled to the specimen. Ultrasonic signals were recorded for each environmental condition.

Damage was introduced by either drilling a single through-thickness hole of increasing diameter (specimens #1 and #3) or machining a through-thickness edge notch of increasing length (specimen #2). Ultrasonic signals were recorded after each incremental enlargement of the hole or notch in order to simulate growth of a defect. The final defect sizes are shown in Fig. 4.

For all of the signals from the three specimens, the start time was 10 µs and the total time window was 1000 µs. This window is sufficient to capture most of the energy of the ultrasound field. Note that the 1000 µs time window is equivalent to a longitudinal wave in aluminum traveling 6350 mm, which is over 40 times the longest dimension of each specimen. For reference, the calculated first arrival of the longitudinal wave (head wave) occurs at 16.3 µs, the first shear arrival is at 32.4 µs, and the Rayleigh wave arrival is at 34.8 µs. These arrivals, although not obviously identifiable, are consistent with the recorded waveforms, and no attempt was made to identify additional arrivals due to the large number of combinations of edge reflections. The diffuse nature of the recorded signals is evident even at very early times.

Fig. 5 shows the signals from specimen #1 corresponding to nominal environmental conditions, an increase in temperature, a partially wetted surface, and introduced damage corresponding to a 6.35 mm drilled hole. The general trend and appearance of these signals are very similar, as is true for all of the recorded signals for all three specimens, although subtle differences are clearly evident. There are no obvious characteristics of the signals in the time and frequency domains that distinguish damage from environmental changes. The diffuse nature of the signals is the dominating characteristic, which is caused by the large number of internal reflections.

V. Results

Data are analyzed using the three methods described previously: time-domain differencing, spectrogram differencing, and local temporal coherence. For each specimen, a common reference signal is used for all three methods, corresponding to room temperature and all surfaces undisturbed (free, clean, and dry).
Fig. 4. Illustrations of three specimens machined from aluminum plate (thickness of 6.35 mm). (a) Specimen #1, rectangular plate with through hole. (b) Specimen #2, rectangular plate with through notch. (c) Specimen #3, square plate with through hole.

A. Time Domain Differencing

Two time windows are considered, one encompassing the entire signal from 10 to 1010 µs and the other from 510 to 1010 µs. The temporal residual energy for each time window is calculated as per (2)–(5) for all of the measured signals from the three specimens based upon a room temperature reference. Results are shown in Fig. 6 for the three specimens in the form of scatter plots. The temporal residual energy for the entire 10 to 1010 µs window is the abscissa and the temporal residual energy from 510 to 1010 µs is the ordinate. Points designated as environmental correspond to changes in surface conditions; there were no such points for specimen #3. Note that, in all three plots, the points corresponding to damage are intermingled with those due to temperature and surface condition changes, indicating that neither of these temporal residual energy parameters is effective for detection of damage.

Fig. 7 shows plots of temporal residual energy for the 10 to 1010 µs window versus flaw size for the three specimens; data from environmental changes are not included. Note that, for all three specimens, the temporal residual energy is strongly correlated to defect size. With only a few exceptions, this parameter is monotonic with defect size, with somewhat of a plateau effect for larger defects. This result is significant because it indicates that, if the signals resulting from damage can be discriminated from those due to environmental changes, the size of the defect can be estimated from the temporal residual energy.

B. Spectrogram Differencing

Spectrograms were calculated for all of the signals for the three specimens using the entire 10 to 1010 µs time window and a frequency range from 0 to 3.5 MHz. This frequency range was selected to encompass almost all of the
energy of the signals; typical center frequencies were approximately 200 kHz, but significant energy was present up to about 2.5 MHz. Spectrograms were globally normalized as per (10), and the corresponding spectral residual energy relative to the room temperature reference signal was obtained using (11). Similarly, time-normalized spectrograms were calculated as per (12) along with the corresponding time-normalized residual energy. Results are shown in Fig. 8 in the form of scatter plots in which the spectral residual energy is the abscissa and the time-normalized residual energy is the ordinate. Note that the two parameters are highly correlated for all three specimens, showing that the locally normalized spectrograms offer little if any new information. Unlike the data from the time-domain differencing parameters, there is some separation between points due to damage and those due to environmental changes. For large values of either parameter, some of the damage points are separated from those due to temperature and surface condition changes.

Fig. 9 shows plots of spectral residual energy versus flaw size for the three specimens. As for the temporal residual energy, this parameter is strongly correlated to defect size, particularly for smaller defects, and thus also could be used to estimate defect sizes. For specimens #2 and #3, there
is much more of a plateau for larger defect sizes than is apparent for the temporal residual energy results of Fig. 7.

C. Local Temporal Coherence

Data are analyzed by computing the local temporal coherence between measured signals and the corresponding room temperature reference signal. Fig. 10 shows the envelope of the local coherence for four signals from specimen #1: temperature increase, temperature decrease, surface condition change, and introduced damage. Fig. 11 shows the corresponding peak coherence and delay plots for these four cases as calculated from (21) and (22), respectively. Note that the delay data of Fig. 11(b) are clipped to ±4 μs. Several observations can be made from these plots:

- The peak coherence for the temperature changes drops somewhat as a function of time, and the delay increases or decreases linearly, which is in agreement with results obtained by Weaver and Lobkis [6].
- The peak coherence for the wetted surface drops somewhat as a function of time, but the delay does not deviate significantly from zero and does not follow an obvious pattern.
**Fig. 10.** Envelope of local temporal coherence for specimen #1 signals relative to reference signal. (a) Undamaged, temperature of 32°C. (b) Undamaged, temperature of 14°C. (c) Undamaged, partially wetted surface. (d) Introduced damage, 6.35 mm through hole.

**Fig. 11.** Peak coherence and delay curves for the data of Fig. 10. (a) Coherence peak. (b) Coherence delay.

- The peak coherence for the introduced damage drops significantly as a function of time. The delay does not deviate significantly from zero, except when the peak coherence drops below about 0.6, in which case the two signals are incoherent and the computed delay is no longer meaningful.

These observations suggest that the change in peak coherence, \( P_1 \) of (21), is a potential discriminator between damage and environmental changes, whereas \( P_2 \), the slope of the delay versus time curve, is an indicator of a temperature change. These two parameters are calculated for the data from all three specimens and are displayed as scatter plots in Fig. 12, where \( P_2 \), the delay slope, is the abscissa, and \( P_1 \), the peak coherence change, is the ordinate.

The data in Fig. 12(a) illustrate the effects of temperature, surface condition changes, and damage on both the delay slope and the peak coherence change. The damage points all are clustered near a delay slope of zero; but the peak coherence change varies from near zero to a maximum of about 0.36. This increase in peak coherence corresponds to increasing damage (hole diameter for this specimen). Temperature changes show the opposite behavior.
Fig. 12. Local coherence parameters. (a) Specimen #1. (b) Specimen #2. (c) Specimen #3.

Fig. 13. Relationship between peak coherence change and flaw size. (a) Specimen #1. (b) Specimen #2. (c) Specimen #3.
TABLE II  
Summary of Results from Spectrogram Differencing.  

<table>
<thead>
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<th>Specimen number</th>
<th>Largest defect misclassified</th>
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<tbody>
<tr>
<td>#1</td>
<td>3.57 mm diameter hole</td>
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<tr>
<td>#2</td>
<td>1.91 mm length notch</td>
</tr>
<tr>
<td>#3</td>
<td>3.97 mm diameter hole</td>
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TABLE III  
Summary of Results from Local Temporal Coherence.  

<table>
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<tr>
<th>Specimen number</th>
<th>Largest defect misclassified</th>
</tr>
</thead>
<tbody>
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<td>3.18 mm diameter hole</td>
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<tr>
<td>#2</td>
<td>1.91 mm length notch</td>
</tr>
<tr>
<td>#3</td>
<td>3.57 mm diameter hole</td>
</tr>
</tbody>
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with a large variation in delay slope coupled with a smaller variation in peak coherence change. The temperature data points from left to right (negative to positive delay slope) correspond to increasing temperature. The data points corresponding to surface condition variations exhibit intermediate behavior, showing irregular variations in both delay slope and peak coherence change. This general behavior is the same for the other two specimens. Note that, for specimen #3, there were no surface condition changes, and the smallest defect size was larger than for the other two specimens (minimum hole size of 3.57 mm). The data from all six transducer pairs are shown on the same plot.

Fig. 13 shows plots of the peak coherence change versus flaw size for the three specimens. The general trend is that peak coherence change increases as defect size increases. Thus this parameter could be used to estimate defect size in addition to defect detection. However, results from specimen #3 show a decrease in peak coherence change for larger defects, indicating that this relationship may not hold for larger defects.

VI. Discussion of Results

Of the three methods considered, the time-domain differencing approach is the least successful for detecting damage, showing essentially no ability to separate flaws from environmental changes regardless of specimen or type of defect (Fig. 6). As many researchers have discovered, simple time-domain differencing is destined for failure because environmental changes have as big, if not bigger, effect on diffuse signals as even significant damage. However, if only signals due to damage are considered, there is good correlation between the temporal residual energy and flaw size (Fig. 7). Thus, time-domain differencing should be considered for defect sizing.

The spectrogram approach offers a higher likelihood for successful damage discrimination because it does take into consideration the time-varying nature of the signals and is not sensitive to phase differences. For all three specimens, the larger defects can be separated from temperature and surface condition changes by either of the two residual energy parameters considered (Fig. 8). These two parameters are highly correlated and offer similar discriminatory capabilities. A measure of performance is the largest defect that is misclassified using a detection threshold equal to the largest value of spectral residual energy for an environmental change; results are summarized in Table II. The spectral residual energy correlates well with defect size (Fig. 9), particularly for small defects, but appears to reach a plateau as the defect size increases.

The peak coherence change provides the best separation of damage from environmental changes (Fig. 12). It is clear that the separation efficacy depends upon the degree of environmental changes that must be considered. As for the spectrogram approach, a measure of performance is the largest defect that is misclassified using a detection threshold equal to the largest peak coherence change for an environmental change; results are summarized in Table III. For all three specimens, the peak coherence change method is able to classify smaller defects than the spectrogram approach. For both approaches, if the detection threshold were lowered, smaller defects would be detected but environmental changes then would be misclassified as damage, which is the usual tradeoff between detection capability and false alarms.

For both specimens #1 and #2, the surface condition changes were considered to be mild to moderate in terms of the percentage of the exposed surface area that was affected, with specimen #2 having the more severe changes. Consider that environmental changes are changes in boundary conditions, and that a sufficiently severe environmental change modifies the structure such that the baseline waveform is no longer applicable. The net result is that, for any structure, there exists an environmental change that is severe enough that it will not be distinguishable from structural damage using the methodology presented here. This observation also indicates the need to consider sensor placement, data fusion, tracking of time history, and use of inspection data, in conjunction with controlling and monitoring surface conditions, in order to reduce the number of false alarms caused by extreme environmental changes.

All of the structural damage data presented here was obtained at near room temperature, as is evident in the grouping of the data points near zero time delay in Fig. 12. If the damage data had been recorded at different temperatures, there would have been a much larger scatter in time delay because of the time stretching (or compression) due to the temperature change. These observations suggest that better discrimination may be possible if a baseline signal at the same temperature is used; this work is in process.

The defect detection capability is similar for the three specimens, with somewhat improved sensitivity for detection of the notch versus the holes. Detection thresholds for the three specimens also are similar for both the spectro-
gram and local coherence methods. These similarities are perhaps not surprising given that the specimens are similar, but they do suggest that detection thresholds may be set independently of the expected flaw type and location.

Not specifically considered were the effects of center frequency and bandwidth on the peak coherence results. For a given percent bandwidth, a higher center frequency will result in a narrower cross-correlation peak with greater sensitivity of its amplitude to signal distortion. Increased frequency should lead to increased sensitivity to damage, but also increased sensitivity to environmental changes. Because thresholds for damage detection are set by observing peak coherence changes for environmental effects, it is reasonable to conjecture that frequency effects will be self-calibrating, at least to some degree. Previous work showing quadratic frequency dependence for both temperature changes [27] and small average motions of scatterers [25] indicates that this may be the case, but experimental verification should be attempted.

VII. Summary and Conclusions

Time-domain differencing, spectrogram differencing, and local temporal coherence of diffuse ultrasonic signals have been considered as means of generating metrics for discriminating damage from environmental effects such as temperature and modest surface condition changes. The peak coherence between a measured signal and a reference signal is a quantitative measure of how much the shape of the signal has changed compared to the reference as a function of time from the transmit pulse; this analysis method provides the best discrimination for the data shown here. The change in peak coherence is a generalized metric of damage that is insensitive to the specific structure and type of location of damage to be detected. Once a signal has been classified as resulting from a defect, a number of parameters calculated via the three methods correlate well with defect size with the most promising being the temporal residual energy. This overall methodology is very attractive for structural health monitoring because of the inherent volumetric coverage of the diffuse ultrasonic waves combined with practicality of implementation for a wide variety of structures. The disadvantage of this approach is that extreme changes in surface (boundary) conditions can be mistaken for damage. If surface conditions cannot be controlled or monitored, it is expected that using multiple sensors, incorporating time history information, and combining monitoring with appropriate inspection will lead to an acceptably low false alarm rate. Future work should consider these issues.

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