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Diffuse field full matrix capture for near surface ultrasonic imaging

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ABSTRACT

This article reports a technique for near-surface ultrasonic array imaging. Information equivalent to an undelayed full matrix of inter-element responses is produced through cross-correlation of a later time diffuse full matrix. This reconstructed full matrix lacks the nonlinear effects of early time saturation present in a directly acquired response. Consequently the near-surface material information usually obscured by this effect is retrieved. Furthermore it is shown that a hybrid full matrix formed through a temporally weighted sum of coherent and reconstructed matrices allows for effective near-surface and bulk material imaging from a single direct-contact experimental realisation.

1. Introduction

The response of an ultrasonic transducer in pulse-echo operation contains nonlinear effects caused by physical limitations of acquisition systems which obscure early time acoustic information. This response is characterised firstly by the finite time associated with the switch from transmission to reception operation, combined with the saturation from remnants of the initial activation (e.g. ultrasonic reverberation within the transducer) and nonlinear electronic recovery process. This problem is compounded when using ultrasonic arrays for which the close proximity of elements leads to saturation of neighbouring elements through electrical and mechanical cross-talk. The consequence of this is to effectively blind an ultrasonic inspection system to the area immediately in front of the array. In common engineering materials this blind region can extend to several mm and is therefore not insignificant.

This may be mitigated in part through the introduction of a stand-off medium (sometimes referred to as a delay line) between the transducer and specimen. This has undesirable effects, namely a reduction in acoustic energy transmitted to the specimen and the potential introduction of additional refracted modes which may induce imaging artefacts. Furthermore this is not always possible in applications which require low-profile, embedded or permanently bonded transducers. Access to early time responses also opens up potential applications for super-resolution imaging as it may allow evanescent fields local to sub-wavelength scatterers to be interrogated directly. Consequently, it is desirable to remove the effects of saturation and element cross-talk without requiring a stand-off medium.

There are a large number of approaches to ultrasonic array imaging. Historically this was achieved using classical beamforming [1], in which the phase delays are applied to the near-simultaneous transmission of elements. This creates a designed interference pattern inside a material, typically to achieve steering or focusing. Images can be generated by sweeping through steered angle or transmission aperture. A more recent approach is the application of delay laws in post-processing to sequentially acquired array data [2]. This allows for the application of much more sophisticated imaging algorithms. Notable examples include dynamic focusing [3,4], plane wave imaging [5] and the wave number algorithm [6]. Another class of imaging algorithm uses principles of singular value decomposition and time reversal which can obtain super-resolution imaging [7]. Recent advances have also allowed imaging using nonlinear elastic modalities [8,9]. Regardless of the approach taken to imaging, since the near-surface information is lost through saturation none of these techniques can accurately image this near-surface region when applied in direct contact. The approach proposed here is to recover near surface information through cross-correlation of diffuse fields.

Some sufficient time after transmission of sound into a bounded system, through the effects of multiple scattering and reflections, the field will appear to homogenise to a diffuse-like state. Although statistically the field may be considered uniform (neglecting weak localisation effects [10]), spatial phase correlations persist within a diffuse field. It has previously been shown [11,12] that ensemble averaging the cross-correlation of response at two points within

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a diffuse field will reproduce the heterogeneous Green's function between the two points. Practically the ensemble average may be approximated through multiple excitations at different source locations or cross-correlation of different temporal windows.

This has found application particularly in the fields of seismology and geo-physics [13–18]. By cross-correlating the coda of seismic events recorded at monitoring stations, the direct response between the stations is obtained. Through this, a virtual array of emitters and receivers is formed. The recovery of Green's functions from diffuse fields has generally been considered of little relevance for non-destructive testing applications since if sound can be recorded at a point then it is trivial to also transmit sound at the same point, thereby allowing direct responses to be obtained explicitly. There is however a potential application in using the process to reveal information obscured by the operating limitations of the acquisition systems.

The nonlinear effects that obscure early time information in ultrasonic measurements are only present within a directly acquired signal. Whereas near-surface information is only present within the obscured region of a direct acquisition, it is implicitly contained throughout the diffuse field and may be retrieved through cross-correlation. It is shown here that signals equivalent to an undelayed full matrix of ultrasonic array data can be recovered from the diffuse field. Crucially this omits effects of early time saturation, allowing for near-surface imaging to be achieved from direct contact measurements.

2. Full matrix reconstruction

Full matrix capture is the process of sequential acquisition of responses for each transmitter-receiver element pair of an ultrasonic array which are then collated to form the so-called full matrix [2]. Typically, phase delays are then applied in post-processing, under an assumption of linear superposition, to emulate the interference effects of equivalent physical beam forming. Through this, sophisticated imaging may the achieved without the prohibitively long acquisition time which would be required with parallel element transmission. Here the time domain responses of the full matrix shall be denoted $h_{i,j}(t)$, where the first and second indices correspond to transmitting and receiving elements respectively. Specifically $h_{i,j}(t)$ shall be reserved for a conventional coherent full matrix in which time zero of the recorded window coincides with the transmission time. The diffuse full matrix, obtained by initiating recording some sufficiently long time, t_r, after transmission, has previously been used in this form for nonlinear ultrasonic imaging [19]. Although it may be considered to simply be a later window of the matrix $h_{i,j}(t)$, here we will denote the diffuse full matrix $d_{i,j}(t)$ in order to make the distinction clear. If both have a window length of T, the spectra of the coherent and diffuse full matrices are $H_{i,j}(\omega) = \int_0^T h_{i,j}(t)e^{i\omega t}\,dt$ and $D_{i,j}(\omega) = \int_{t_r}^{t_r+T} d_{i,j}(t)e^{i\omega t}\,dt$respectively.

The aim here is to process the diffuse full matrix $d_{i,j}(t)$ in a such a way as to obtain a matrix equivalent to $h_{i,j}(t)$ but that is not polluted by the nonlinear measurement artefacts that obscure early time data. In order for the Green's functions to effectively emerge through cross-correlation, a practical approximation must be made to the theoretical ensemble average. Since the full matrix contains responses for the transmission of each individual element, source averaging equal to the number of elements can be applied.

A reconstructed full matrix, $g_{i,j}$, is obtained by cross-correlating the responses of element i with that of element j, averaged over all transmitting elements. For an N element array, in the time domain this may be written as follows

$$h_{i,j}(t) \approx g_{i,j}(\tau) = \frac{1}{N}\sum_{k=1}^{N}\int_{t_r}^{t_r+T} d_{k,i}(t)d_{k,j}(t+\tau)\,dt. \quad (1)$$

This is a consequence of representation theorem [20]. Equivalently, in the frequency domain this is simply the inner product of each element response spectra and the conjugate of the other, again averaged over transmissions as follows

$$G_{i,j}(\omega) = \frac{1}{N}\sum_{k=1}^{N} D_{k,i}(\omega)\bar{D}_{k,j}(\omega). \quad (2)$$

Reconstruction improves with longer window length T but at the expense of computation time. The selection of reception delay t_r is a compromise between field diffusivity and signal to noise ratio. The larger the contribution of noise, the more averaging operations are required to produce the same quality of reconstruction. A rigorous analysis of the influence of these parameters on Greens function recovery has been given by Weaver and Lobkis [11].

In practice the cross-correlation need only be performed over the bandwidth required for subsequent imaging. What is obtained is an approximation to the inter-element Green's functions convolved with the element transfer functions. This may be regarded as a time reversal operation in that, through processing, the later time diffuse full matrix is transformed to the equivalent matrix with no reception delay.

3. Near surface imaging

Full matrix reconstruction was applied to the inspection of a rectilinear aluminium block with artificial near-surface defects. The block had dimensions of 30 × 50 × 20 mm and the defects were a series of 0.5 mm diameter holes machined between 0.5 and 2 mm from one edge at 0.25 mm increments. Inspection was conducted using an Imasonic (Voray-sur-l'Ognon, France) 128 element ultrasonic array with a nominal centre frequency of 10 MHz and pitch of 0.3 mm, interfaced with a Micropulse FMC model array controller manufactured by Peak NDT Ltd (Derby, UK). The array was gel-coupled (with <0.1 mm gel thickness) to the sample surface closest to the defects and both coherent and diffuse full matrices acquired. Captured windows lengths were 60 μs, corresponding to 3000 data points captured at a sampling rate of 50 MHz. The diffuse full matrix was acquired with a reception delay, t_r, of 1 ms.

An example of typical time traces, for $i = j = 64$, of each full matrix is shown in Fig. 1. Each time trace is normalised to its peak value. It can be seen that the early time signal obscured in the coherent capture has been recovered in the reconstructed data. This preservation of near-surface information is clearer when viewing a larger subset of the full matrix. Fig. 2 shows the pulse-echo responses for each element ($i = j$), equivalent to a B scan. Here individual near-surface reflections for each hole can easily be discerned in the reconstructed full matrix. The apparent periodicity in the back wall amplitude seen in Fig. 2(a) is a shadowing effect caused by the near-surface holes blocking transmission of sound in those locations.

The first back wall reflection, present at approximately 10 μs can be seen in the reconstructed data however not as clearly as when obtained directly. Additionally, the smaller secondary hole reflections are less well resolved in the reconstructed field. As a consequence of the finite number of averaging operations, the recovery of Green's functions within the reconstructed full matrix will always be imperfect and less accurate than directly acquired signals. As such, while near-surface information is obtained more accurately using reconstruction, the response from the interior of the part is better acquired from conventional coherent capture. A