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Ultrasonic imaging through thin reverberating materials

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Abstract

Imaging through anisotropic or highly heterogeneous materials is challenging for the existence of strong boundary and volume reverberations. To image small cracks or flaws in a reverberating thin layers, high resolution techniques are needed in both temporal and spatial domain, so that the reverberation can be suppressed to some level. In this paper, the reverberation suppression performance of the total focusing beamforming method (TFM) was evaluated by simulation and real data processing. The results showed that the more the focusing point moves away from the array central line, the more multi-reflections can be suppressed. Furthermore, TFM combined with adaptive processing greatly improves the small flaw detection performance. Test results on real samples confirmed the robustness and reverberation suppression capability of the TFM imaging method.

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Keywords: Total focusing method, thin-layer, reverberation suppression

1. Introduction

Techniques for ultrasonic imaging and flaw detection in bulk materials made from homogeneous isotropic materials can be considered quite mature, and efficient and affordable equipment for inspection is readily available. Recently, a new ultrasonic imaging method termed as TFM, Holmes et al. (2005); Dave et al. (2011); Jobst and Connolly (2010), has received more and more attention. With the advanced full matrix capture (FMC) data acquiring technique by which each transducer transmits signal sequentially and meanwhile all the transducers are receivers, TFM has much more data information (3D data) than the traditional phased array ultrasonic transducers (PAUT), so that the resolution and noise suppression performance can be improved greatly.

However, imaging through anisotropic or strongly heterogeneous materials, such as fiber reinforced polymers or coarse-grained metals is still challenging and there is a clear need for further development. The reason is that the traditional delay-and-sum based imaging modalities cannot handle the coherent backscatters from these materials very well, since it is really difficult to compute the exact time delays for all the transmitter-receiver combinations. A special case is when the material is either thin or composed of several thin layers. Under this condition, the received signals are affected by multiple reflections from within the layered structure, rather than from randomly located scatterers (e.g. grains, fibers, etc). If not suppressed, these type of multi-reflective reverberations will effectively mask any flaws present in the material. Often, the structure of a healthy material is reasonably well-known, meaning

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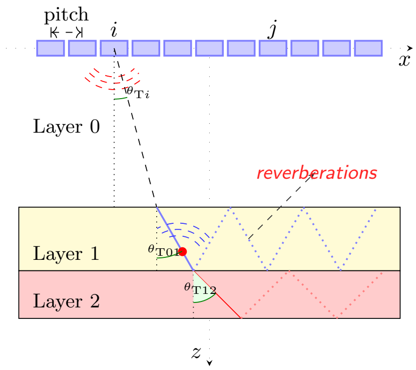


Fig. 1: Multi-layer model.

that the reverberation in a healthy sample can be modeled, Hägglund et al. (2009); Brekhovskikh (1980). Thus, a reference signal can be obtained in beamforming to suppress the reverberations. However, this reference signal based cancellation algorithms are always sensitive. In this paper, we first give the reverberating multi-layer model and the imaging algorithms. Then, the k-Wave model, Treeby and Cox (2010), was used to evaluate the reverberation suppression performance of TFM and adaptive TFM algorithms. Finally, real data from two test blocks with semi-circular holes were analyzed.

2. Thin layer ultrasonic imaging

2.1. Multi-layer model

Multi-layer model is depicted as in Fig. 1. Main parameters: the sound speed c_l and the layer thickness h_l in the lth layer, the number of sensors N, array pitch d (inter-element spacing), transmit angle at ith sensor: θ_{Ti}, transmission angle from ith layer to jth layer: θ_{Tij}.

2.2. TFM beamforming

TFM beamforming coherently add together all the echoes from possible transmitter-receiver pairs. Ideally, for a N-element array, the output SNR gain would be $\mathbf{20}\log N$, comparing to the conventional array gain of $10\log N$. So it is expected that TFM can achieve the reverberation suppression capability for thin layers.

Consider a single-layer material immersed in water (coupling media, ”Layer 0”), the transmission angle from water to the layer is: $\theta_{T01} = \arcsin\left(c_1 \sin(\theta_{Ti})/c_0\right)$. Then the path length from the ith transmitter to the crack at (x_c, z_c) is:

$$h_0 \tan(\theta_{Ti}) + (z_c - h_0)\tan(\theta_{T01}) = x_c - x_{Ti} \tag{1}$$

By some arithmetic manipulation, we define an cost function $g(\theta_{Ti})$:

$$g(\theta_{Ti}) = h_0 \tan(\theta_{Ti}) + (z_c - h_0) \times \frac{(c_0/c_1)\sin(\theta_{Ti})}{\sqrt{1-(c_0/c_1)^2 \sin^2\theta_{Ti}}} - (x_c - x_{Ti}) \tag{2}$$

θ_{Ti} can be optimized by *root-finding* algorithms, and the initial value for θ_{Ti} is set as the sight-of-line angle from the transmitter to the crack, i.e. $\theta_{Ti}(0) = \arctan((x_c - x_{Ti})/z_c)$.

Knowing the transmit angle from the sensor to the crack and the receive angle from the crack to the sensor, the path length/time delay can be easily computed. (2) can be generated to multi-layer scenarios. Thus, the delay-and-sum TFM beamforming output at arbitrary position (x, z) can be written as

$$I(x,z) = \sum_{m=1}^{N}\sum_{n=1}^{N} \alpha_{mn}(x,z) e(\tau_{mn}(x,z)) \tag{3}$$

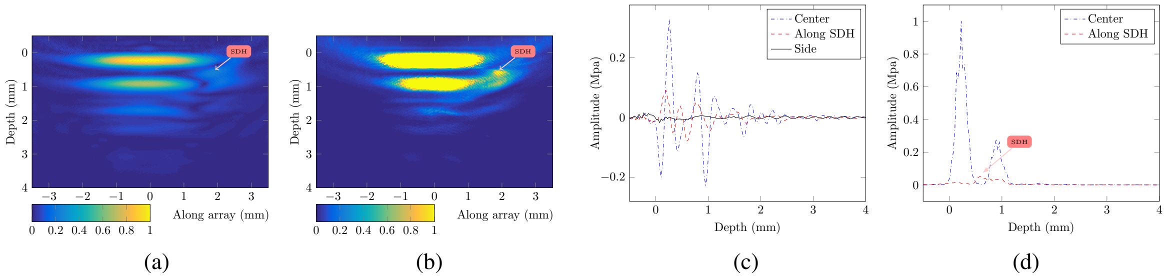


Fig. 2: (a) CTFM image; (b) ATFM image; (c) Slices of CTFM; (d) Slices of ATFM.

where e is the echo data, $\alpha_{mn}(x,z)$ controls whether the path from the mth transmitter to the crack, then to the nth receiver has a physical realizability. $\tau_{mn}(x,z)$ is the corresponding time delay.

$$\alpha_{mn}(x,z) = \begin{cases} 1 & \text{if } \tau_{mn}(x,z) \le N_e, \\ 0 & \text{if } \tau_{mn}(x,z) > N_e. \end{cases} \tag{4}$$

2.3. *Adaptive TFM beamforming (ATFM)*

Minimum variance distortionless response (MVDR) adaptive beamforming can improve the spatial resolution and reject the interference by minimizing the output power while maintaining the signal response undistorted. The proposed ATFM algorithm uses the steered MVDR (STMV) combined with diagonal loading.

The (i,l)th element of the steered array covariance matrix is:

$$\hat{\boldsymbol{R}}_{[i,l]}(f) = \sum_{m=1}^{N}\sum_{n=1}^{N} \alpha_{mn} \cdot \left(\mathcal{F}\{e_{im}\}(f)\mathcal{F}^*\{e_{nl}\}(f)e^{j2\pi f(\tau_{im}-\tau_{nl})}\right) \tag{5}$$

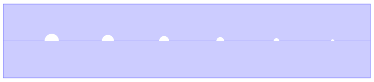
where the (x,z) dependence was omitted to simplify the expression, and $\mathcal{F}\{\cdot\}$ denotes Fourier transform. Then, the output STMV spectrum is: $P_{\mathrm{STMV}}(f) = \sum_m \sum_n \hat{\boldsymbol{R}}^{-1}(f)$.

3. Simulation results

The k-Wave toolbox, Treeby and Cox (2010), was used to model the multi-layer echoes. The simulation parameters are as in Table. 1. Fig. 2 shows the imaging results by conventional TFM (CTFM) and ATFM methods. It was demonstrated that for extremely thin layers, the CTFM method cannot detect the weaker defeats, however, ATFM still works well due to its reverberation suppression capability.

Table 1: Simulation parameters

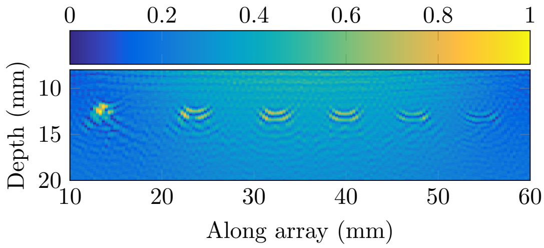
	c_p (m/s)	α_p (dB/(MHz^2 · cm))	ρ (kg/m^3)
Layer 0 (Water)	1482.5	0.0022	1000
Layer 1	2330	0.0042	2000
Layer thickness	1mm	SDH radius	0.1mm
No. of sensors N	8	Pitch / Frequency	0.5mm / 2MHz



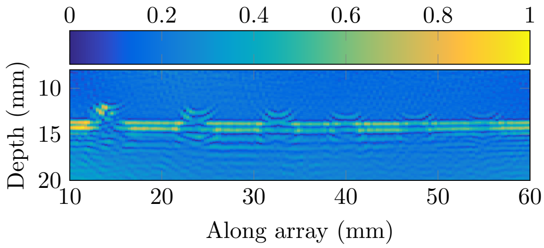
(a)

(b)

Fig. 3: Two-layer materials with semi-circular SDH's. (a) (10+10)mm; (b) (10+1)mm.



(a)



(b)

Fig. 4: TFM results: (a) (10+10)mm layer; (b) (10+1)mm layer.

4. Experimental results

Two-layer bonded steel blocks with a few radius-decreasing semi-circular side-drilled holes along the interface were tested using a 128-element 5MHz transducer array, and 80 sensors were used in beamforming. The side-view of the testing blocks are depicted as in Fig. 3.

Fig. 4 shows the TFM results. All six semi-circular holes were detected, both thick and thinner layer, see Fig. 4b.

5. Conclusions

In this paper, we demonstrated the reverberation rejection capability of the total focusing beamforming method in ultrasonic testing. For much thinner layers, adaptive beamforming and delayed line can be used to improve the weaker flaw detection performance. Model-based reverberation canceling combined with TFM beamforming would be nicer.

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