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A SUPER-RESOLUTION APPROACH OF THE TOTAL FOCUSING METHOD FOR RESOLVING CLOSE FLAWS

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ABSTRACT

This paper proposes a method to enhance the resolution of images computed from Full Matrix Capture (FMC) datasets widely used in Non-Destructive Evaluation (NDE). The resolution of standard techniques such as Total Focusing Method (TFM) that do not account for the impulse response of transducers is limited. The proposed model exploits the instrumental signature of the transducers in order to link linearly the FMC dataset to the reflectivity of the material. An ill-posed inverse problem is hence formulated due to the limited bandwidth of the transducers. The final image is obtained iteratively by inverting the model using a sparse prior representing the small number of scatterers in the specimen under test. Experimental results are given in order to compare the proposed method with the well-known TFM. A specific application of close flaw separation is presented and shows that the proposed approach is able to resolve two close scatterers separated by $\lambda/4$.

Keywords: ultrasonic imaging, total focusing method, inverse problem, regularization, resolution, GPU.

NOMENCLATURE

τ	Time of flight
u_i, v_j	Abscissa of emitter and receiver
N_{el}	Number of elements
$N_x N_z$	Number of pixels
N_t	Number of time samples per signal
λ	Wavelength
c	Speed of sound (m/s)
$\boldsymbol{y}$	FMC data
$\boldsymbol{H}$	waveform matrix
$\boldsymbol{o}$	reconstructed image

1. INTRODUCTION

Imaging techniques using phased array probes are commonly used in ultrasonic imaging for their ability to build images. Conventional imaging techniques only focus at few points in the material by applying a delay law in the hardware. These methods have been outperformed by Delay-and-Sum (DAS) techniques that focus the signals at each point of a region in post processing [1]. The industrial use of these new methods is made possible thanks to the growth of Graphic Processing Unit (GPU) [2] and ultrasonic hardware capabilities. Still, due to the impulse response of the transducers or Point Spread Function (PSF) [3], a single scatterer in the material gives oscillations in ultrasonic images, which limits the resolution of such methods.

The proposed approach includes the PSF in order to build a waveform matrix that links the reflectivity of the media to the ultrasonic raw data. The reconstruction of the reflectivity at each point from data collected by transducers pulsing and receiving in a limited range of frequencies is an ill-posed inverse problem [4]. In NDT, the final image contains only few scatterers with a small size, thus a sparse *a priori* information is relevant in order to regularize the problem [5,6,7]. The result is then obtained by minimizing a penalized least squares criterion within an iterative procedure [8].

In this paper, the inverse approach is presented in the context of FMC acquisition and is compared to the well-known Total Focusing Method on experimental data from an aluminum block containing Side Drilled Holes (SDH).

2. INVERSE METHOD

2.1 The Total Focusing Method

The FMC data acquisition consists in firing successively with each transducer, the reflected echoes being acquired with all elements of the probe. The TFM is a standard process to produce ultrasonic image from FMC data [9]. For each pixel (x_k, z_l) of a discrete grid, the proper time of flight is computed

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for each emitter/receiver pair. In a homogeneous media inspected in contact, the time of flight reads:

$$\tau(\mathrm{i},\mathrm{j},\mathrm{x_k},\mathrm{z_l}) = \frac{\sqrt{(\mathrm{x_k}-\mathrm{u_i})^2+\mathrm{z_l^2}}+\sqrt{(\mathrm{x_k}-\mathrm{v_j})^2+\mathrm{z_l^2}}}{\mathrm{c}}. \quad (1)$$

Then, all signals are summed for each pixel at the proper time of flight as follows:

$$O_{\mathrm{TFM}}(x_k, z_l) = \sum_{i=1}^{N_{el}} \sum_{j=1}^{N_{el}} y_{i,j}\big(\tau(x_k, z_l, i, j)\big). \quad (2)$$

This operation can be realized in real time by parallelizing the computation on GPU [2].

2.2 Direct Model

Each signal can be modelled as a convolution between the PSF and the reflectivity of the media under test [3 ,10]. Thus, a convolution matrix $\boldsymbol{H}$ can be built to link the discrete directivity $\boldsymbol{o}$ of the material to the FMC signals $\boldsymbol{y}$ [11]:

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{o} + \boldsymbol{n}, \quad (3)$$

where $\boldsymbol{y} \in R^{N_t N_{el}^2}$ is the vectorized data, $\boldsymbol{o} \in R^{N_x N_z}$ is the vectorized reflectivity sequence. $\boldsymbol{n} \in R^{N_t N_{el}^2}$ stands for the noise and model errors and each column of $\boldsymbol{H} \in R^{N_t N_{\mathrm{el}}^2 \times N_x N_z}$ gathers the signature in the data of a single, pointwise, scatterer located at the corresponding position in the medium.

2.3 Inversion

From Equation (3), retrieving the reflectivity of the media $\boldsymbol{o}$ from the knowledge of the ultrasonic raw data $\boldsymbol{y}$ formulates an inverse problem [4]. Due to the frequential selectivity of the probe, the problem is ill-posed and must be regularized by introducing a priori information depending on the desired properties in the final solution $\boldsymbol{o}$. Thus, the reflectivity of the media is obtained by minimizing iteratively the following criterion:

$$J(\boldsymbol{o}) = \|\boldsymbol{y} - \boldsymbol{H}\boldsymbol{o}\|^2 + \phi(\boldsymbol{o}), \quad (4)$$

where $\phi(\boldsymbol{o})$ is the regularization function. Sparse a priori have been widely used in ultrasonic imaging [5,6,7] and are particularly adapted to the reconstruction of few small scatterers. Thus, the chosen penalization function is composed of a sparse term. In order to ensure spatial smoothness between close pixels in the solution, another penalization function is added to the criterion:

$$\phi(\boldsymbol{o}) = \mu_1\|\boldsymbol{o}\|_1 + \mu_2\|\boldsymbol{D}\boldsymbol{o}\|^2, \quad (5)$$

where $\boldsymbol{D}$ is a matrix operator computing differences between neighboring pixels, μ_1 and μ_2 are the regularization parameters that balance between the data fitting term and the prior knowledges. The non-differentiable criterion is minimized with FISTA algorithm [8].

3. RESULTS

In this part, the proposed method is confronted to the TFM. The goal of the first experiment is to show the resolution improvement from experimental data acquired at 3 MHz from an aluminum block presented on Figure 1a. The reconstruction grid is centered on 3 SDH of 1mm diameter at 30 mm depth.

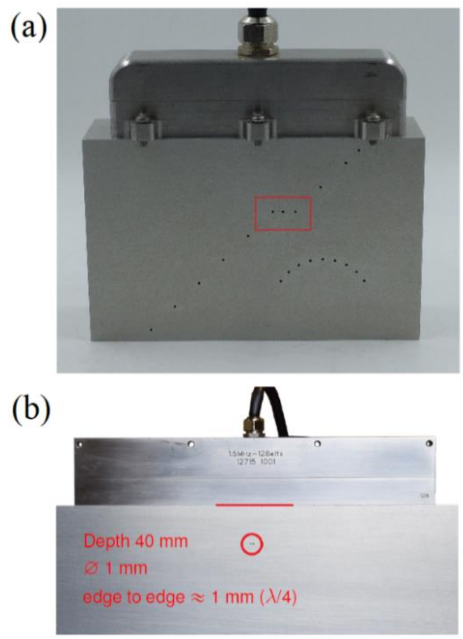

FIGURE 1: (a) First acquisition on an aluminum block. The reconstruction grid is framed in red around 3 SDH. (b) Second acquisition on an aluminum block containing 2 close SDH circled in red.

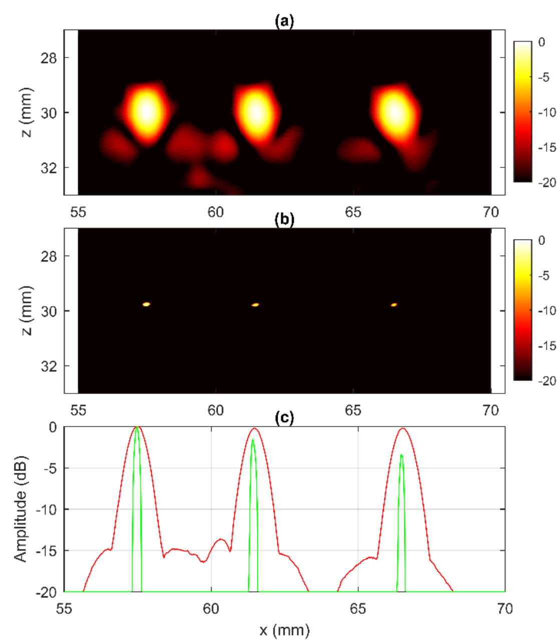

FIGURE 2: (a) TFM reconstruction and (b) Inverse method reconstruction in log scale. (c) Maximum amplitude of the two reconstructions along z axis.

	Lat. Res. (mm)			Ax. Res. (mm)		
SDH	#1	#2	#3	#1	#2	#3
TFM	0.97	1.00	1.05	1.40	1.43	1.39
INV	**0.24**	**0.20**	**0.19**	**0.11**	**0.10**	**0.10**

TABLE 1: Lateral and axial resolutions at -6dB computed on the TFM and inverse method reconstructions presented in Figure 2.

The results are presented in Figure 2 and corresponding metrics are computed in Table 1. From this experiment, it is clear that the inverse method outperforms the TFM in terms of lateral and axial resolutions.

The second experiment consists in resolving two close SDH of 1 mm diameter located at 40 mm depth, distant from 1 mm edge to edge presented on Figure 1b. The probe used to acquire the data is pulsing around 1.5 MHz, which means that the wavelength in aluminum is around 4.2mm. Moreover, the inter-element space is 2 mm, i.e. twice the distance between the two flaws. Figure 3 shows the TFM and inverse method reconstruction in log scale. The two SDH are not resolved in the TFM image where only one big spot is visible. In the Inverse method reconstruction, the two flaws are resolved and the maxima of the two spots is distant of 1.50 mm.

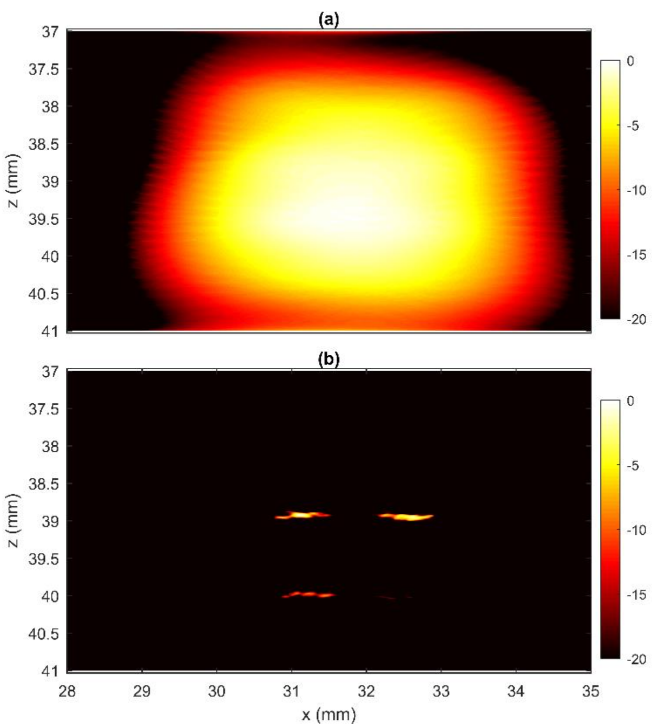

FIGURE 3: (a) TFM reconstruction and (b) Inverse method reconstruction in log scale

4. CONCLUSION

An inverse problem approach applied to FMC data has been presented. The method consists in inverting a linear model that accounts for the instrumental response of transducers using a sparse prior. Applied to SDH in an aluminum block, the proposed method improves significantly the resolution on the reconstructed image and is able to separate close flaws up to $\lambda/4$. This work is still in progress in order to integrate complex propagation properties that accounts for the PSF distortion into the model, the final purpose being the improvement of resolution and signal to noise ratio in scattering materials.

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