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IMPROVED DEFECT DETECTION FOR ULTRASONIC NDE AND IMAGING BASED ON ANGLE OF ARRIVAL (AOA) ESTIMATION IN DIMENSION-REDUCED BEAM-SPACE

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ABSTRACT

Robust defect detection in the presence of grain noise originating from material microstructures is a challenging yet essential problem in ultrasonic non-destructive evaluation (NDE). In this paper, a novel method is proposed to suppress the gain noise and enhance the defect detection and imaging. The defect echo and grain noise are distinguished through estimating the angle of arrival (AOA) of the returned echo and evaluating the likelihood that the echo is reflected from the point where the array is focused rather than from the random reflectors like the grain boundaries. The method explicitly addresses the statistical models of the defect echoes and the spatial noise across the array aperture, estimates the AOA and the likelihood in the dimension-reduced beam-space, and determines a weighting factor based on the likelihood. The factors are then normalized and utilized to correct and weight the NDE images. Experiments on industrial samples of austenitic stainless steel are conducted with a 5MHz transducer array, and the great benefits of the method on defect detection and imaging in ultrasonic NDE are validated.

Keywords: ultrasonic imaging, non-destructive evaluation, AOA estimation, beam-space transformation

1. INTRODUCTION

Robust defect detection in the presence of grain noise is a challenging yet essential problem in ultrasonic non-destructive evaluation (NDE), which has attracted significant attention in recent decades. A variety of coarse-grained materials such as alloy and austenitic stainless steel offer attractive properties like high-temperature strength or excellent resistance to corrosive environment, and thus are widely used to build components like ducting, combustion cans, and transition liners in a range of key industrial sectors such as energy, transportation, oil and gas, nuclear, and aerospace. However, when these materials and structures are inspected using ultrasound, the flaw echoes are usually contaminated by high level grain noise originating from the material microstructures, furthermore, the grain noise is time-invariant, highly correlated with the flaw echoes, and demonstrates similar spectral characteristics.

Several techniques have been investigated to reduce grain noise and enhance defect detection through exploiting the key differences between defect echoes and grain noise. The defect echo typically has a coherent structure with energy mainly scattered from a single spatial point, while the grain noise is spatially distributed throughout the insonified resolution cell. The observation has motivated adaptive beamforming [1], and spectral diversity techniques.

In this paper, a novel approach is proposed to enhance the defect detection in ultrasonic imaging and nondestructive inspection based on estimation of the arrival angle of the echo impinging on the transducer array. With the angle of arrival (AOA) estimation, this method distinguishes a flaw echo from grain noise via evaluating if the echo is reflected from the array focal point or from other directions due to random reflectors like grain boundaries. Different from beamforming and coherence factoring techniques, this method explicitly addresses the statistical model of spatial noise across the array aperture and the correlation between the target signal and the interfering echoes from random reflectors, and estimates the likelihood that the echo originates from the focal point of the transducer array. In particular, the AOA estimation is performed in a dimension-reduced beam-space. As the signal processing complexity is directly related to the dimension of the data, obviously the beam-space processing may significantly reduce the computation cost. Furthermore, as demonstrated in the literature [2], a well-designed beam-space transformation may improve the AOA estimation performance in terms of a reduced estimation bias, a lower resolution threshold, and a lower sensitivity to the wave-front distortion, which are all important for ultrasonic NDE applications.

2. MATERIALS AND METHODS

2.1 BS Transformation Design

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A key challenge in beam-space array processing is the design of the linear transformation **T**. Several approaches to transformation design have been proposed based on the respective criterion. The maximum estimation accuracy (MEA) technique [3] evaluates the distance between the full dimension element-space Cramer-Rao bound (CRB) and the associated beam-space CRB, and derives a transformation where the ES CRB is asymptotically attained in the beam-space. MEA produces excellent BS AOA estimation, but is sensitive to out-of-sector interference. To address the undesired interferers, Li and Lu [4] propose a subspace projection based technique to reject interference by incorporating nulls towards the undesired emitters, which is robust and effective if the interferers are closely clustered.

To illustrate the effectiveness of BS processing for ultrasonic NDE and imaging, in this paper, we employ the MEA technique for BS transformation design, which is simple and straightforward to implement. Essentially, MEA evaluates the transformation's in-sector estimation accuracy, and is defined by measuring the distance between the full dimension ES CRB and the associated BS CRB obtained with **T** over the spatial sector of interest Θ [3],

$$\eta(\mathbf{T}) = \left(\frac{\int_{\Theta} \mathrm{CRB}_{ES}(\theta)\, d\theta}{\int_{\Theta} \mathrm{CRB}_{BS}(\theta, \mathbf{T})\, d\theta} \right)^{1/2}. \qquad (1)$$

The AOA estimation CRB is well studied and defined in the literature.

2.2 Factor Evaluation and Imaging

The maximum likelihood estimation algorithm is employed in this work, considering its excellent performance to address AOA estimation in harsh environment involving highly correlated (or even coherent) sources, low SNR, and short number of snapshots (there is single snapshot in the ultrasonic NDE scenario) [5]. An index is introduced to evaluate the likelihood that the echo is originated from the array focal point. As an example, the spatial spectrum (likelihood) obtained from a data vector is normalised and illustrated in Fig. 1. The minimising solution is achieved at 90 degree corresponding to the focal point. The BS spatial sector is defined and illustrated by the dashed line, and the AOA estimation is only evaluated within the spatial sector of interest i.e. at [70, 110] degree (which thus requires less computation). Assume that the array focal region is defined and illustrated by the dotted line, eg at [88, 92] degree, a factor is defined by

$$F = \frac{mean\ fitness\ within\ the\ focal\ region}{mean\ fitness\ outside\ the\ focal\ region}. \qquad (2)$$

The factor achieves a higher value if the data vector is returned from a point with a major reflector; on the contrary, if the echo comes from spatially distributed sources, the value of the factor will be lower.

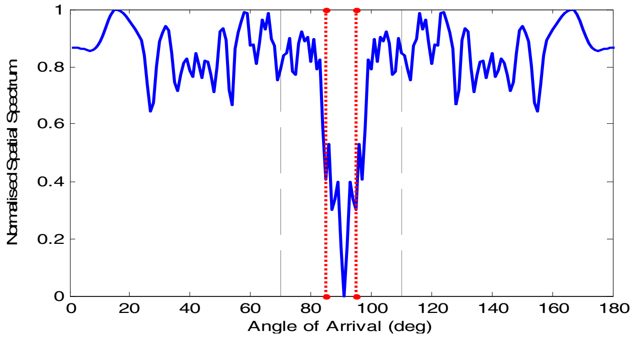


FIGURE 1: EXAMPLE NORMALIZED SPATIAL SPECTRUM

3. RESULTS AND DISCUSSION

The performance of the proposed method for enhanced defect detection in ultrasonic NDE inspection and imaging is demonstrated and analysed in this section. A 64-element transducer array with 5MHz central frequency and a test sample from a coal-fuelled power plant generator end ring with a thickness of around 55 mm made of austenitic stainless steel are utilised in the experiment. Due to the size of microstructure grains, stainless steel is demonstrated to be highly scattering to the 5 MHz ultrasound, and results in dominant and significant grain noise and pretty low SNR.

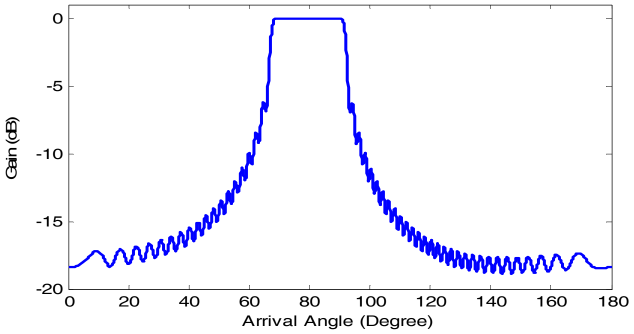


FIGURE 2: BEAM PATTERN OF THE DESIGNED BEAM-SPACE TRANSFORMATION

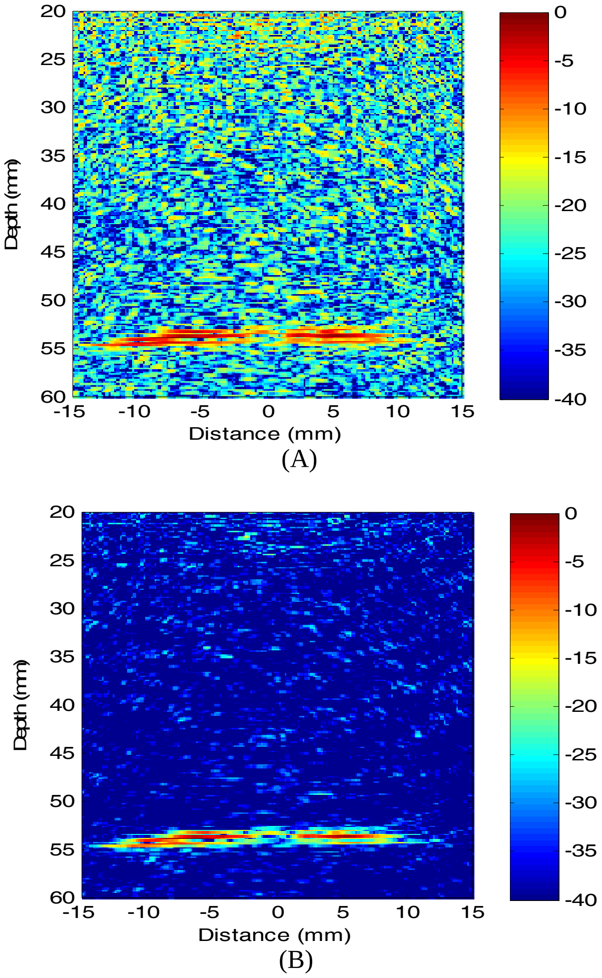
The beam-space transformation is designed using the MEA technique [3]. The BS spatial focusing sector is specified to be an interval [70, 90] degree. The proper dimension of the beam-space is determined by evaluating the performance measure (1) over the spatial interval of interest. The beam-space transformations with different dimension are constructed, and the performance measure over the interval [70, 90] degree is evaluated. As the BS dimension k increases, the BS performance gets closer to the element space performance in terms of the AOA estimation CRB. When k=16, $\eta(k) = 1$, thus the BS dimension is chosen to be 16. The beam pattern of the designed BS transformation is demonstrated in Fig. 2. The echoes within the spatial interval [70, 90] degree will be passed through the transformation with a unit gain, and the interference from other directions out of the spatial sector will be attenuated. The further away from the focusing sector, the more attenuation will be applied, for instance, the echoes from the interval of [110, 180] degree will be attenuated by 15-20 dB, which thus have less impact on the estimation within the BS focusing sector.

Fig. 3(a) shows the image obtained with total focusing method (TFM) [1]. In order to apply the proposed method to the FMC data, each A-scan waveform is appropriately delayed to focus at the point of interest, the pre-focused data vector is processed with the BS transformation to reduce the dimension from 64 to 16 (while maintaining the same AOA performance), and then the maximum likelihood AOA estimator is applied to the BS data vector and the likelihood is measured for the spatial interval of [70, 90] degree. In the experiment, the focal region is set to be 2 degrees, which means that any echoes within the range of [88, 90] degree are considered to be on-axis, and the others are considered to be off-axis. The factor is evaluated using equation (2) for each point in the imaging region, and then normalized. In addition, the amplitudes of the TFM image in Fig. 3(a) are multiplied with the weighting factors point by point, and the corrected image is shown in Fig 3(b).

As can be seen from Fig. 3, the TFM image of the stainless steel sample in Fig. 3(a) is quite noisy when the 5MHz ultrasound is utilized. The back-wall reflection is visible, but the SNR is not high. In Fig. 3(b), the factors corresponding to the back-wall region demonstrate higher values, and the other areas produce lower coefficients, due to the fact that in the back-wall region, a larger portion of the received energy originates from the point where the array is focused, but in a region without dominant reflectors, the received energy is more evenly distributed spatially across the angle domain. When the factors are multiplied with the amplitudes and in the weighted image, the grain noise is greatly reduced in comparison to the raw TFM image, and at the same time, the back-wall is well retained with consistent strength.

4. CONCLUSION

This paper presents a novel approach to suppress the gain noise and improve the defect detection in ultrasonic NDE and imaging, based on the AOA estimation in the dimension-reduced beam-space. The method distinguishes the flaw echoes from grain noise in the spatial domain via evaluating the arrival angle of the returned echo. The technique is validated with experiments on the industrial samples of austenitic stainless steel with a 64-element 5MHz transducer array. It has been observed that the echoes from the back-wall of the specimen produce much higher factor values than that of grain noise, and the TFM images are improved by more than 20dB when the amplitudes are weighted using the normalized likelihood as a factor. The computation complexity is reduced as a result of transforming the data into a lower dimension space.



(A)

(B)

FIGURE 3: IMAGES OF AUSTENITIC STAINLESS STEEL SAMPLE. (A) TFM IMAGE, (B) WEIGHTED TFM IMAGE WITH FACTORS DETERMINED BASED ON AOA ESTIMATION.

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