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A time-domain synthetic aperture ultrasound imaging method for material flaw quantification with validations on small-scale artificial and natural flaws

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ABSTRACT

A direct time-domain reconstruction and sizing method of synthetic aperture focusing technique (SAFT) is developed to improve the spatial resolution and sizing accuracy for phased-array ultrasonic inspections. The basic idea of the reconstruction algorithm is to coherently superimpose multiple A-scan measurements, incorporating the phase information of the sampling points. The algorithm involves data mapping and in-phase summation according to time-of-flight (TOF). Data mapping refers to the process of placing each of the sampling points to a two-/three-dimensional grid that represents the geometry model of the object being inspected. The value for each of the cells of the grid is a summation of all sampling points mapped into the cell. A sizing method based on the concept of 6 dB-drop is proposed to characterize the flaw boundary. The extents, orientation and the shape of the flaw can then be inferred to provide more information for life assessment calculations. Lab experiments are performed using a 10 MHz phased-array ultrasonic transducer to collect data from a cylinder material block with closely spaced artificial flaws and from a material block with a natural flaw. The developed method is used to process the experimental data to characterize the flaws. Using the developed method, the improvement of spatial resolution is observed. Results indicate that four closely spaced 0.794 mm-diameter flat-bottomed holes are clearly identified, and the quantification of size and orientation of the natural flaw is very close to the actual measurement made from digital microscopy after cutting the testing piece apart.

1. Introduction

The development in sensor technology over the past few decades has significantly advanced the capability of ultrasonic transducers in terms of central frequency, flexibility and reliability. In particular, phased-array (PA) traducers can interrogate an planar area or a three-dimensional (3D) volume due to its ability to electronically steer the beam axis. Comparing with traditional monolithic transducers which can only interrogate a line segment, PA transducers can greatly reduce the time required for inspections of large material blocks [1]. As a result, the use of ultrasonic non-destructive evaluation (NDE) has become a standardized tool for quality and safety assurance in many industrial sectors [2–5]. Conventional testing data files store rectified echo intensities and the phase information is limited or not retained. Sizing of a flaw indication is made using the method of distance-gain-size (DGS) [6] with the maximum echo amplitude of the flaw region for conservativeness. The method of DGS reports the size of the flaw in terms of the diameter of an equivalent disk reflector, i.e., a flat-bottomed hole (FBH) or a side-drilled hole (SDH), perpendicular to the beam axis. Because the physical orientation, shape, and extents of the flaw cannot be estimated using the method of DGS, a large uncertainty in sizing is introduced for fatigue life prediction and structural integrity assessment [7]. The sizing uncertainty and uncertainties from material properties and fatigue load conditions will finally propagate to the remaining life assessment results through damage evolution models [8,9]. To reduce the life assessment uncertainty, improving the accuracy of flaw sizing is a key component. In condition-based maintenance for large and complex engineering structures, a more reliable flaw sizing method allows for more accurate estimation of maintenance intervals to minimize the life-cycle service cost. To achieve the minimal life-cycle cost, an

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imaging method is desired to characterize the extents, orientation, and shape of a flaw.

The spatial resolution of ultrasonic NDE generally improves with the increasing center frequency and the increasing bandwidth. The major limitation of the high-frequency ultrasound is its attenuation, reducing the penetration limit and signal-to-noise ratio (SNR) [10]. In practice, the detection and evaluation of flaws also depends highly on the data acquisition and post processing techniques [11,12]. To improve the resolution of monolithic transducers, synthetic aperture focusing technique (SAFT) was proposed [13]. The original ultrasonic applications of SAFT followed the applications of improving the lateral resolution of airborne radar systems. The idea is to scan the antenna over a large area to synthesize a large effective aperture to improve the resolution [14–16]. For industrial ultrasonic NDE applications using SAFT, full waveform echo data are required so the phase information can be retained. When using a monolithic transducer for SAFT, the angle of incidence (i.e., beam axis) must be manually carefully set to be perpendicular to the defect reflector at different inspection positions. The inconvenience can be avoided when using a PA transducer because it can sweep the angle of incidence over a predefined range automatically. It is almost sure that, regardless of the position of the transducer, some of the angles of incidence are (approximately) perpendicular to the defect reflector when the sweeping interval of angles is small enough. Recent development on industrial ultrasonic imaging enhancement has drawn a great attention in signal processing using SAFT. Spies and Jager [17] presented an investigation of synthetic aperture focusing for defect reconstruction in anisotropic composite materials. Pignone [18] reported an NDE system for rotor bore inspection integrating the SAFT post-processing method. Li et al. [10] proposed an adaptive weighting technique based on a focusing-quality index to suppress sidelobes and improve the performance of SAFT. Baby et al. [19] presented the experimental work demonstrating the feasibility of ultrasonic SAFT to obtain improved detection and sizing of vertical/inclined simulated cracks underneath different claddings. Brekow et al. [20] developed the defect sizing on power plant components using PA-based SAFT. Spies and Rieder [21] applied the SAFT to enhance the probability of detection of defects in strongly attenuating materials. Boehm et al. [22] reported the investigation of crack shape analysis using SAFT and a comparison of the SAFT analysis between modeling and phased-array measurements. Zhang et al. [23] reported a method for sizing a defect with a size less than the wavelength by measuring the scattered wave field around the defect. Prager et al. [24] provided a comparative study of two defect sizing techniques, SAFT and time-of-flight diffraction, using a reactor pressure vessel mock-up. Most of the published work has been focused on the theoretical aspect of signal processing for visualization purposes, and flaws (or features) are relatively large. Few studies have been reported to formulate a complete SAFT processing and sizing methodology for realistic industrial applications with small-scale flaws.

The objective of this study is to develop a direct time-domain imaging method of SAFT for quantification of small-scale flaws in industrial applications. Here the small-scale is considered as a length comparable to the wavelength of the ultrasound. NDE for critical industrial components such as turbine rotors and disks usually demands accurate quantification of small-scale flaws. The ideal goal of the development is to reduce the sizing uncertainty, thus improving the life assessment reliability and supporting a more economical condition-based maintenance. The basic idea of the proposed time-domain SAFT is made via a reconstruction process to coherently superimpose multiple A-scan data at all locations, incorporating the phase information of the sampling points. The reconstruction process involves mapping and summation. Mapping refers to placing each of the sampling points into a three-dimensional grid that represents the geometry model of the object being inspected. To estimate the extents, orientation, and shape of a flaw indication, a 6 dB-drop method is proposed to identify the flaw boundary. To demonstrate the overall methodology and verify its effectiveness and accuracy, lab testing is performed to obtain data from material blocks having artificial and natural flaws. The study is organized as follows. First, the direct time-domain SAFT reconstruction method is introduced. The key parameters of the spatial discretization for grid generation is explained, and the detailed algorithm is provided for actual implementation. Next, the sizing method is proposed based on the concept of 6 dB-drop to characterize the flaw boundary. The extents, shape, and orientation of the flaw can then be estimated using the sizing method. Following that, experimental validation is performed to demonstrate the overall methodology and verify its effectiveness. Material blocks with artificial flaws and a natural flaw are used. The material block with the natural flaw is cut apart after the inspection to perform the microscopy measurement. SAFT results on flaw extents and orientation are compared with actual measurements.

2. Time-domain reconstruction of SAFT

The concept of SAFT is illustrated in Fig. 1, where a PA transducer is moved along the scan surface. At each of the data acquisition positions the probe irradiates a number of A-scan signals and then receives the corresponding scattered echo signals. The sampling data of the sound field acquired by the transducer at one position can overlap with the sampling data acquired at other positions. For instance (as shown in Fig. 1) the echo of the flaw from the interrogating A-scan with a certain angle of incidence (denoted as dashed lines) at location A overlaps with those produced at positions B and C. Each of these locations can be viewed as an aperture element. The basic idea of SAFT reconstruction is to process the virtual aperture elements as a unit by summing individual virtual aperture elements point by point across the entire interrogating area or volume. The A-scan signals of a PA transducer hitting the flaw location can formulate a virtual large aperture which is centered over the flaw, as illustrated by the three dashed lines (in Fig. 1) from positions A, B, and C. In this case, the size of the virtual large aperture is the distance between A and C. In reality the size of the virtual aperture can be much large than the size of the probe when the angle sweeping range of the PA probe is properly set. If

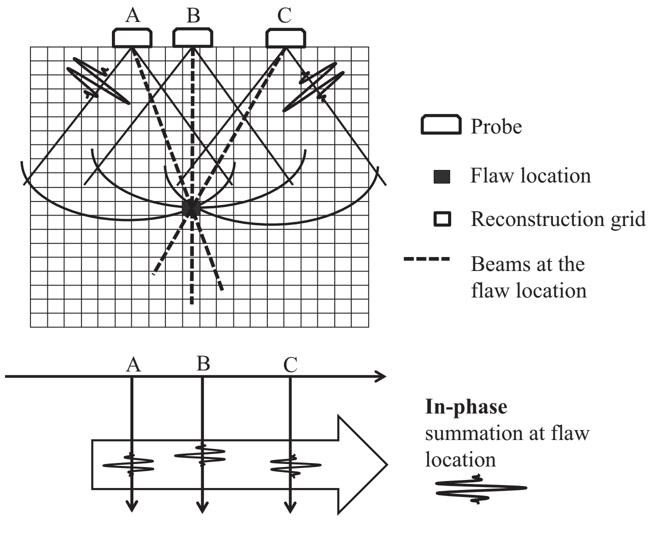

Fig. 1. SAFT illustration.