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A high resolution approach for nonlinear sub-harmonic imaging

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ABSTRACT

Nonlinear sub-harmonic phased array imaging is used to visualize closed cracks. Sub-harmonic imaging has broader beam width than that of input frequency imaging due to its longer wavelength. If the broad beam width results in low image resolution, it can be hard to determine the locations of cracks. Various methods have been developed to enhance the resolution, and MUltiple SIgnal Classification (MUSIC), in particular, is an old but well-established way to do so. A form of sub-harmonic imaging that implements MUSIC is presented here. A numerical simulation was used to compare the proposed method with a conventional one, and MUSIC gave narrower beam width. Experiments also demonstrated that MUSIC could improve the resolution of sub-harmonic imaging.

1. Introduction

Acoustic nonlinear imaging is a technique that depicts parameters associated with acoustic nonlinearity, which is known to be induced mainly by nonlinear elastic behavior of media [1,2] or nonlinear phenomena from un-bonded contact interfaces [3]. In particular, contact nonlinearity due to defect nonlinearities (e.g., micro-scale pores or cracks) has been a great help in improving the size of detectable crack or recognizing small fractured cracks invisible to linear NDE techniques [4]. Nonlinear phenomena at un-bonded interfaces have also long been attracted to many researchers. Buck et al. [3] experimentally observed harmonic generation at fatigue cracks as well as at un-bonded interfaces. Richardson [5] formulated the harmonic generation at un-bonded interfaces with a simple but fundamental 1-D semi-infinite media. Solodov et al. [6] introduced popping nonlinearity to explain nonlinear effects (higher and sub harmonic generation) produced from the contact between separated surfaces under various contact pressures.

Cracks generated in a solid usually go through crack closure due to restraint of the surrounding elastic body [7]. Crack closure typically gives rise to close proximity or even touching of confronting surfaces. With linear ultrasonic inspection it is, therefore, hard to detect the contiguous (or closed) parts due to almost total transmission of incident ultrasonic waves, and this eventually leads to underestimation of crack size [8]. To assess the crack-size more precisely and to localize the closed part visually, nonlinear sub-harmonic imaging [9] was introduced. This was done to overcome the poor characteristics of higher harmonics, which usually have low signal-to-noise ratio due to various background noises [10]. Sub-harmonic generation under various circumstances has been observed experimentally. (For example, see Refs. [11–13].) Sub-harmonic generation at closed cracks was theoretically formulated [14], and Akino et al. [15] observed sub-harmonic generation at fatigue cracks in an aluminum alloy experimentally.

It is certainly more practical to visualize where a closed crack is, than just to know whether there is a closed crack. Nonlinear imaging techniques have mainly been developed in medical imaging, using higher harmonics, over 30 years [16–17]. The use of nonlinear imaging has recently been reported for use in damage detection by nondestructive testing and evaluation. Solodov et al. [18] localized damage with spectral patterns for nonlinear self-modulation and sub-harmonics. Ulrich et al. [19] applied a time reversal mirror to localize a hairline crack as a nonlinear scatterer. A higher-harmonic imaging scheme has also been applied to Inter-Granular Stress Corrosion Crack (IGSCC) in the Ni-based alloy welds widely used in nuclear power plants [20]. More recently, Potter et al. [21] proposed a novel form of nonlinear imaging with a conventional phased array probe by contrasting the energy of a focused beam, which generates acoustic nonlinearity very well, with that of sequentially transmitted waves.

The previous works on the nonlinear imaging were focused on introducing their own way to visualize acoustic nonlinearity. In particular, nonlinear subharmonic imaging [9] has been used to

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show images for sub-harmonic frequency, which is only sensitive to closed cracks, with conventional time-domain beamforming and filtering. Therefore, the sub-harmonic imaging has inherently lower resolution than that of the input frequency due to longer wavelength. (for example, see Ref. [22]) The maximum value of the main-lobe in PA imaging represents a possible crack location, and the main-lobe beam width depends on the frequency of interest. The beam width becomes broader as the frequency goes lower. The broad main-lobe often prevents determination of where the cracks are. For more than half a century, various attempts have been made to improve spatial resolution in array signal processing, and eigen-analysis based on spatial cross-correlation matrix is well-established for providing high resolution [23]. The eigen-analysis method led to a family of algorithms that make use of signal and noise subspace (e.g., MUSIC [24], GEESE [25], ESPRIT [26], MIN-NORM [27]).

In this paper, MUSIC is adopted to improve the resolution of sub-harmonic PA imaging not only because of its multiple source detectability and quantified statistical performance [25], but also because of the similarity between the beamforming (or matched field processing) operator and the spatial correlation matrix [28]. The aim of this paper is first to briefly examine the conventional beamforming mainly exploited in nonlinear sub-harmonic imaging in time domain and frequency domain as well. The underlying mathematical description of MUSIC is presented as well, and implementation of the MUSIC algorithm to nonlinear sub-harmonic imaging is introduced, along with numerical simulation. Next, the experimental set-up for sub-harmonic imaging, and the practical uses of the experimental conditions, is explained. The third aim is to demonstrate that MUSIC provides closed-crack positions with much higher resolution than did previous form of sub-harmonic imaging.

2. High resolution nonlinear sub-harmonic phased array (PA) imaging

2.1. Sub-harmonic PA imaging

Phased array imaging is a technique by which to make images by shifting (or delaying) signal phases and summing the shifted (or delayed) signals. The delay and sum (DAS) is an old but very robust array signal processing algorithm for forming and steering beams [22]. Most phased array imaging techniques for non-destructive evaluation (NDE) are based on the DAS algorithm, and the images are depicted by controlling phases. The PA imaging, therefore, has no frequency selectivity, but it is indispensable for sub-harmonic phased array imaging to draw images for a specific frequency component: half the input frequency from a transmitter.

Sub-harmonic phased array imaging has been developed to visualize phased array images for sub-harmonic frequencies, especially at half the input frequency [9]. It is recommended to separate transmitter from receiver for high power excitation at the exciting (or fundamental) frequency and also for signal acquisition with high sensitivity at the sub-harmonic frequency. This leads to the choice of single crystal-type piezo-electric material as a transmitter, to exclude possible nonlinearity that might arise from the transmitter. The array receiver is used to form images by measuring waves that arrive at different times due to different measurement positions. Fig. 1 shows the transmitting and receiving geometry. A single transmitter at $(x_t,\ z_t)$ generates ultrasonic waves, and then the array receiver placed at $(x_{r_i},\ z_{r_i},\quad i=1,2,3,\ldots,N)$ measures the waves at each element position. Let us denote $u(x_{r_i},\ z_{r_i},\ t)$ as displacement measured, and then the phased array image is obtained by pulling or delaying the signal with respect to the focal point at $(x_f,\ z_f)$ in the zone of interest as shown in Fig. 1.

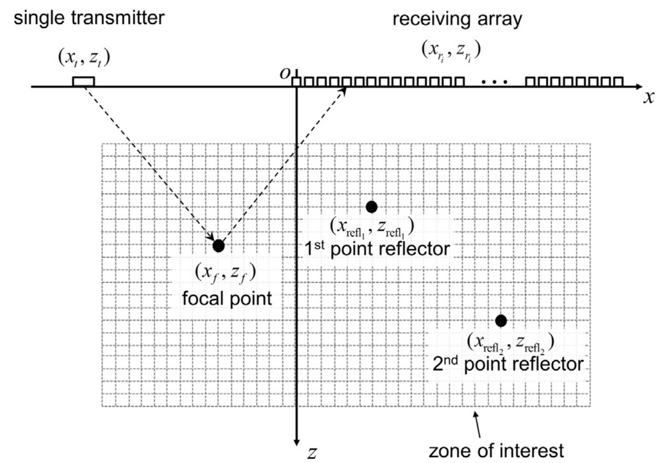

Fig. 1. Phased array geometry of transmitting and receiving for sub-harmonic imaging.

The time delay, with respect to a focal point, is calculated from the geometric relation between the transmitter position and the receiver position. Suppose that ultrasound propagates in a medium that has a speed of propagation (c); then the time required for the wave to reach the receiver at a focal point could be calculated as

$$\Delta\tau(x_{r_i}, z_{r_i}) = \frac{\sqrt{(x_t-x_f)^2+(z_t-z_f)^2}+\sqrt{(x_{r_i}-x_f)^2+(z_{r_i}-z_f)^2}}{c}. \quad (1)$$

The delay-and-sum (DAS) beamformer's output [23] for imaging can be formulated as

$$b(x_f, z_f, t) = \sum_{i=1}^{N} u(x_{r_i},\ z_{r_i}, t-\Delta\tau(x_{r_i},\ z_{r_i})) \quad (2)$$

at each focal point, $(x_f,\ z_f)$. Then, the frequency spectrum is obtained by Fourier transform as

$$\boldsymbol{B}(x_f,\ z_f,\ f) = \int_{-\infty}^{\infty} b(x_f,\ z_f,\ t)e^{-j2\pi ft}dt, \quad (3)$$

which is for convenient frequency selection and envelope imaging. The boldfaced font means that the value is complex. The beam power distribution for the sub-harmonic frequency component can be obtained as

$$\boldsymbol{B}_{sub}(x_f,\ z_f;\ f_{sub}) = \boldsymbol{B}(x_f,\ z_f,\ f)\times \boldsymbol{H}_{sub}(f) \quad (4)$$

by multiplying Eq. (3) with a frequency response function that has the sub-harmonic frequency (f_{sub}) as its center frequency, and excludes the fundamental frequency component. It is often clearer and more recognizable to show an envelope image than that of its own oscillating waveform when the image is complicated [29]. The envelope image is calculated by Hilbert transform as

$$\boldsymbol{b}_{sub}(x_f,\ z_f,\ t) = \int_0^{\infty} \boldsymbol{B}_{sub}(x_f,\ z_f;\ f_{sub})e^{j2\pi ft}df. \quad (5)$$

The magnitude of the complex beam power distribution [30],

$$b_{sub}^{peak}(x_f,\ z_f) = \max_t\left[\left|\boldsymbol{b}_{sub}(x_f,\ z_f,\ t)\right|\right], \quad (6)$$

is the sub-harmonic PA image that we want to get, and the peak value on the image indicates the location of a closed crack.

2.2. High resolution imaging by MUSIC

MUSIC [24] is a well-defined way to make the resolution better using the orthogonal property between deterministic crack-signals