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Nonlinear ultrasound inspections for structural prognosis

*Choon-Su Park[1], Seunghyun Cho[2], Dae-chul Seo[3] and Jun-Woo Kim[4]

[1), 2), 3)] *Center for Safety Measurements, Division of metrology for quality of life, Korea Research Institute of Standards and Science (KRISS), 267 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea*
[4)] *Safety qualification technology center, KHNP Central Research Institute, 1312 Yuseong-daero, Yuseong-gu, Daejeon, Republic of Korea*
[1)] *choonsu.park@kriss.re.kr*

ABSTRACT

It must be of great importance to detect structural defects that may cause catastrophic collapse. Many inspections and monitoring have been made to ensure structural health. It would be practically useful to find defects in an early stage or hidden from conventional inspections for cost-effective and proactive maintenance. Nonlinear ultrasound inspections have been proved to be a promising way to detect hidden cracks, which are not uncovered by linear methods. Second harmonic nonlinear parameter has been well known to characterize micro-structural features in structures. As a classical nonlinear ultrasonic NDE method, second harmonic generation has been widely used to evaluate microstructural change on various materials. In addition, nonlinear sub-harmonic generation as a non-classical nonlinear ultrasonic NDE has been well proved to detect closed cracks that may cause underestimation of crack size. In this paper, we present recent investigation on absolute nonlinear parameter for the classical nonlinear NDE and also on sub-harmonic phased array (PA) imaging for the non-classical NDE. The basic principles on nonlinear phenomena are explained, and experimental verifications were carried out with some actual specimens, which gave practical and also meaningful results.

1. INTRODUCTION

Nonlinear ultrasonic NDE is a method that observes the behavior of ultrasonic waves and estimates nonlinear parameters, which are known to be induced by nonlinear elastic characteristics of media (Breazeale 1963) or nonlinear phenomena from unbonded contact interfaces (Buck 1978). In particular, contact nonlinearity due to pores, precipitates, cracks, etc. (so called, defective nonlinearity) has been a great help in improving detectable crack size or recognizing small fractured cracks invisible by linear NDE techniques (Solodov 1998). In other words, nonlinear ultrasound inspections have been proved to be a promising way to detect hidden cracks from linear methods.

[1)] Senior research scientist (Ph. D)
[2)] Principal research scientist (Ph. D)
[3)] Principal research scientist (Ph. D)
[4)] Researcher

Nonlinear parameter calculated from second harmonic frequency component has been widely used to assess the level of damage for various materials, and it is classified into classical nonlinear ultrasound NDE. The measurement for the nonlinear parameter usually requires a pure single frequency input ultrasound that does not have any second harmonic component. Due to this prerequisite, a delicate experimental setup such as a highly linear signal generator, a transmitter, and a receiver is demanded. In addition, perfect contact condition between the transducers and a specimen is very essential to maintain single frequency input firmly. Otherwise, the measurement may lead to poor experimental repeatability, large deviation of the nonlinear parameter, and, most of all, difficulty in measuring absolute nonlinear parameter. Actually, the second harmonic frequency component is not easy in real situations.

Next, nonlinear sub-harmonic phased array (PA) imaging has been proved to be a method to visualize closed crack that generates the half frequency of input signal. It is certainly more practical to visualize where a closed crack is than just to know whether the closed crack is or not. The sub-harmonic PA imaging inherently has broader beamwidth than that of input frequency due to its longer wavelength. The maximum value of main-lobe in PA imaging represents possible crack location, and main-lobe beamwidth depends on the frequency of interest. The beam width becomes broader as frequency goes lower. Broad beamwidth that leads to low spatial resolution is often hard to identify crack location. For more than half a century, it has been variously developed to improve spatial resolution in array signal processing, and eigen-analysis based on spatial cross-correlation matrix is well-established for high resolution (Johnson 1989).

In this paper, we present a method to measure nonlinear parameter under the assumption the incident ultrasonic wave has not only main exciting frequency but also its second harmonic frequency component caused by the nonlinearity of the instruments and an ill-conditioned contact. A model was made to calculate elastic nonlinear parameter in consideration of second harmonic component of an input incident wave. As for the sub-harmonic imaging, MUSIC (<u>MU</u>ltiple <u>SI</u>gnal <u>C</u>lassification) is adopted to improve the resolution of sub-harmonic PA imaging by using orthogonal property between crack signal and noise based on eigen-analysis.

2. ABSOLUTE SECOND HARMONIC NONLINEAR PARAMETER ESTIMATION

Nonlinear parameter (generally called, β) is formulated with second harmonic component generated from a propagating monochromatic elastic input wave. That is,

$$\beta = \frac{8}{k^2 l}\left(\frac{A_2}{A_1^2}\right), \tag{1}$$

where k is wavenumber, A_2 is second harmonic component after propagating distance l , and A_1 is fundamental wave component incident into a specimen. In case of taking initial 2nd harmonic component into account the nonlinear parameter, the initial 2nd harmonic component at l should be considered as depicted in Fig.1. Then, absolute nonlinear parameter can be obtained as

$$\beta = \frac{8}{k^2 l} \frac{\sqrt{B_2^2 - A_2^2}}{B_1^2}, \tag{2}$$

where B_1 and B_2 are the magnitude measured at l for the fundamental frequency and 2nd harmonic component, respectively.

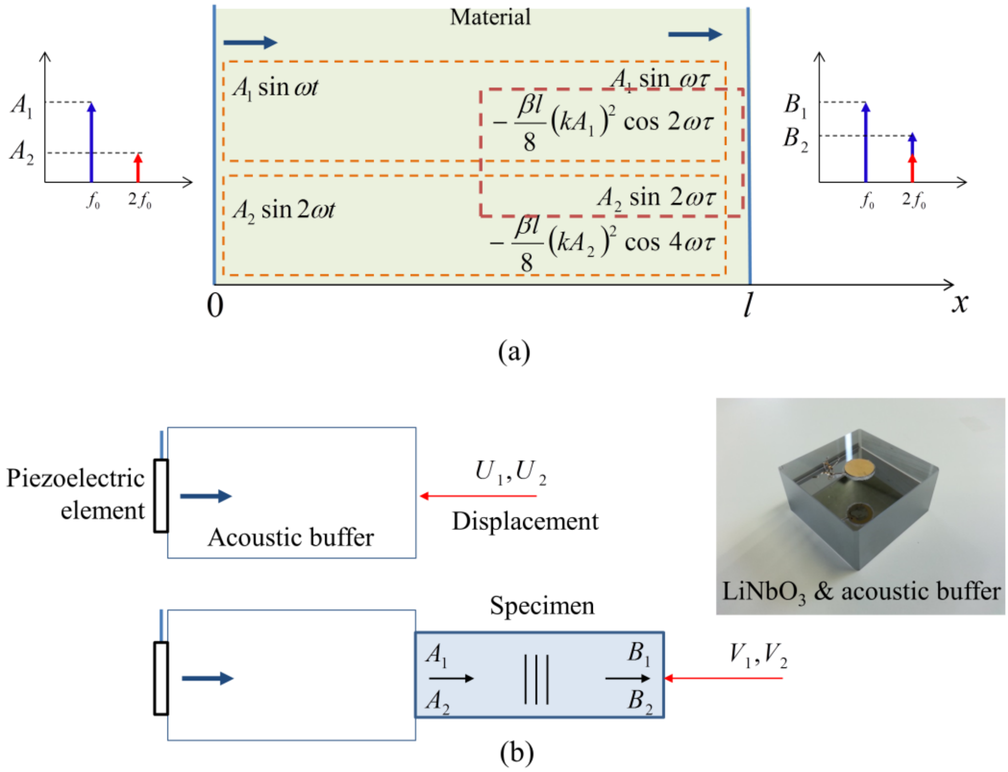

Fig. 1 Absolute second harmonic nonlinear parameter measurement, (a) Conceptual diagram for initial 2nd harmonic component, (b) Schematic diagram for initial 2nd harmonic component measurement.

3. HIGH RESOLUTION SUB-HARMONIC IMAGING FOR CLOSED CRACK DETECTION

Phased array imaging is a technique to make images by shifting (or delaying) signal phases and summing the shifted (or delayed) signals. The delay and sum (DAS) is an oldest but most robust array signal processing algorithm to form and steer beams (Park 2009). Most phased array imaging techniques for non-destructive evaluation (NDE) are based on the DAS algorithm, and the images are depicted by moving phases (Park 2014). The PA imaging, therefore, has no frequency selectivity, but it is indispensable for sub-harmonic phased array imaging (Ohara 2007) to draw images for a specific frequency component, which is the half of input frequency from a transmitter. The beamforming power for the sub-harmonic frequency could be formulated as

$$\boldsymbol{b}_{sub}(x_f, z_f, t) = \int_0^\infty \boldsymbol{B}_{sub}(x_f, z_f; f_{sub}) e^{j2\pi ft} df \ . \tag{3}$$

The peak value on the magnitude of complex beam power distribution,

$$b_{sub}^{peak}(x_f, z_f) = \max_t \left[\left| \boldsymbol{b}_{sub}(x_f, z_f, t) \right| \right], \tag{4}$$

is the sub-harmonic PA imaging that points closed crack location. See more detail derivation in Park (2015).

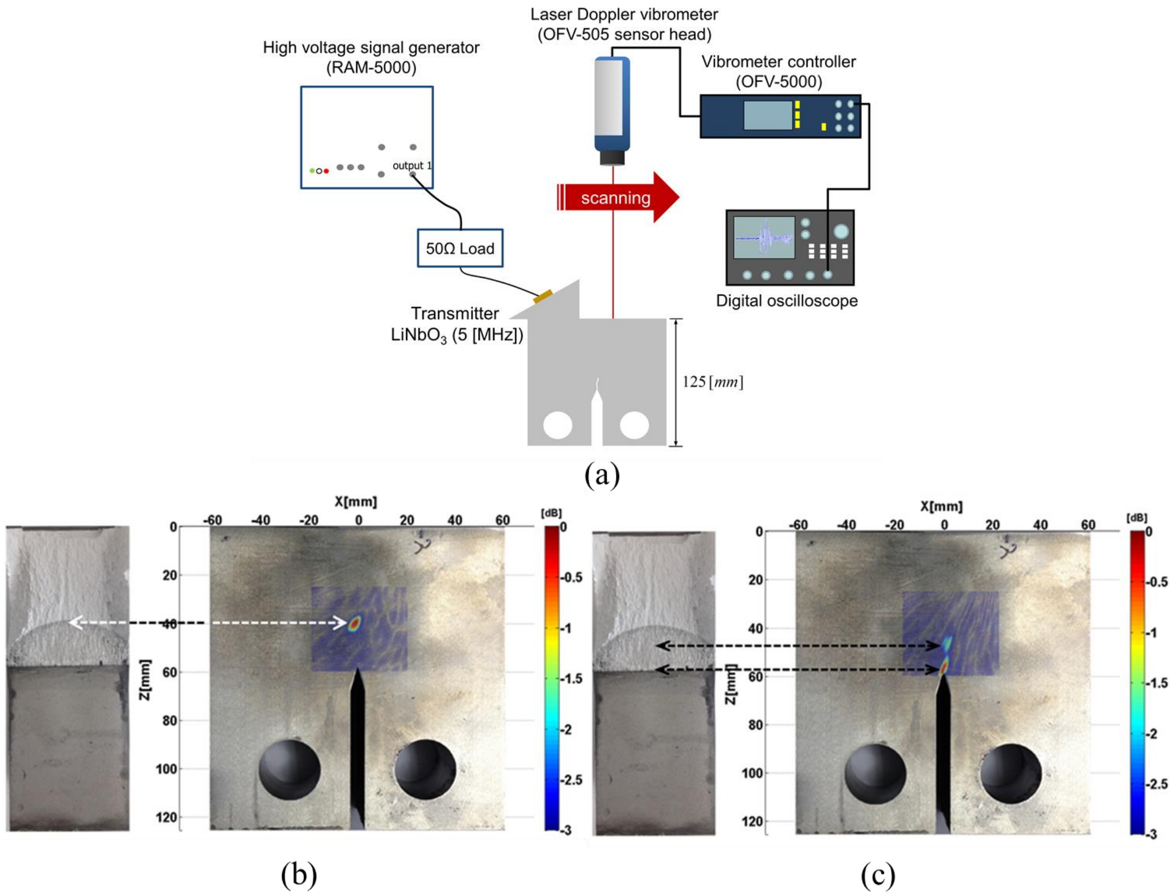

Fig. 2 Measurement system and imaging results, (a) Schematic diagram of experimental apparatus, Cross-section of the specimen with phased array images for (b) Sub-harmonic frequency (2.5 [MHz]) that is assumed to show closed part indicated by white arrow, (c) Fundamental frequency (5 [MHz]) that shows open part indicated by black arrows.

The measurement system is schematically depicted in Fig. 2(a). Fig. 2 (b&c) clearly distinguishes a conventional PA image and a nonlinear sub-harmonic image. It is noted that the conventional PA image shows the maximum peak at the notch tip clearly and another peak that has about -1.2 [dB] less than the maximum peak, which is assumed to be open crack at around 13 [mm] above the notch tip. On the other hand,

Fig. 2(c) does not show any peak at the position that can be seen in Fig. 2(b) and are indicated by black dotted arrows. It is noteworthy that the only and maximum peak of the sub-harmonic image, which is indicated by white arrow, is observed at around 20 [mm] above the notch tip and has broader width than the fundamental peaks. In other words, fatigue crack is assumed to propagate further (7 [mm] in this case) than what can be seen from the conventional PA image.

4. CONCLUSIONS

Nonlinear parameter that takes initial 2^{nd} harmonic component into account is presented. Theoretical formulation for the initial 2^{nd} harmonic component is proposed, and it is noted that additional measurement is necessary for the initial 2^{nd} harmonic component with acoustic buffer. This could provide absolute nonlinear parameter that is able to quantitatively assess the level of damage. Next, a high resolution approach with MUSIC is presented for non-linear sub-harmonic imaging that can detect closed crack in a solid. The MUSIC has been proved to make resolution better by orthogonality between crack signal and noise. The conventional PA image corresponding to the fundamental frequency clearly showed notch tip and a position assumed to be an open crack. Furthermore, the conventional sub-harmonic PA image indicated a point above the linear PA image, and the point is proved to be closed crack by observing the cross-section of the specimen after tearing it apart. In the end, nonlinear second- and sub-harmonic ultrasonic NDE could be applied to detect faults, which cannot be seen by linear method, earlier for structural prognosis.

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