Measurement of wavenumber of wall-thinned plate using spatial local wavenumber filtering

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ABSTRACT

The surface of a shell-type structure can generate cracks or wall-thinning due to corrosion, etc. Those can eventually lead to the fracture of the structure, which can trigger enormous fatality and property loss. Thereby, a laser imaging technology on such structures as thin plate structure or piping whose thickness is relatively thin in comparison to the area, has been steadily studied for the past 10 years. The most typical among the laser imaging technology is the pulse laser imaging. By using the same, a new technology for inspecting and imaging a desired area within a relatively short period of time was developed, so as to scan various structures including the thin-plate structure and piping. However, this method builds image by measuring waves reflected from defects, and has a time delay of a few milliseconds at each scanning point. Moreover, complexity of the systems is so high due to additional components such as laser focusing parts. This paper proposes laser imaging method with increased scanning speed based on excitation and measurement of standing waves in structures. It is shown that defects in a structure can be visualized by generating standing waves with single frequency and scanning the waves at each point by the laser scanning system suggested in this work. To quantitatively evaluate thickness of a plate, wavenumber is calculated by acoustic wavenumber spectroscopy, and relationship between wavenumber and thickness of the plate is established by Rayleigh-Lamb frequency equation. The proposed technique is validated by wall-thinned plates that have constant wall loss and a linear thickness variation wall loss.

1. INTRODUCTION

The excitation method using pulsed laser requires time for the acoustic wave to be scattered and disappear, and a few milliseconds of time delay for each scan point is needed. Therefore, it is very difficult to reduce the scanning time, and the reception using the LDV has low SNR (Signal to Noise Ratio), so a number of repetition processes are needed, which requires additional scanning time (E. B. Flynn, 2014). Also, since it is very important to measure the constant acoustic pressure, the laser should be formed on the flat field, which requires costly optical equipment such as f-Theta lens in front of the LDV. When using a common lens, the focus cannot be adjusted on the working plane (Mikhail, 2014), and the energy density decreases, making it difficult to obtain high SNR. Therefore, f-Theta lens is required to adjust the focus onto every point of the working plane. Finally, estimation of crack length and localization of damage have been done using various signal processing techniques (Lee, Chia, Park, & Jeong, 2012; Lee, Chia, Shin, Park, & Yoon, 2011; Lee, Chong, Jeong, & Kong, 2011), quantitative evaluation of wall thinning loss of plate like structures has not been done yet (Lee, Jeong, Ciang, Yoon, & Lee, 2010). Plate like structures and pipelines are often exposed to corrosion because of the environmental conditions as well as the properties of the transported media. In order to prevent fatalities and property loss of structures, they are inspected at regular intervals using NDE tools such as ultrasonic inspections, AE, and radiographic testing, etc. Most important issue is quantitative evaluation of interrogated structures using NDE tools. Up to date, even though laser imaging technique is very promising tools for resolving this problem, little research of quantitative wall loss of structures has been done.

To resolve such disadvantages, Flynn of LANL (Los Alamos National Laboratory) suggested the local wavenumber estimation method based on quantitative approach (E. B. Flynn, Chong, Jarmer, & Lee, 2013). By using the local wavenumber estimation method, impact damages on composite and fatigue cracks in aluminum were detected (E. Flynn, Haugh, & Lopez, 2015; E. B. Flynn, 2014). Idea of this method is came from frequency-wavenumber domain filtering proposed by Ruzzene (Ruzzene, 2007). Forward and backward propagation wave can be separated in frequency-wavenumber domain using full wavefield data. Based on this principle, symmetric and non-axisymmetric mode are also separated, and wanted mode can be extracted using full wavefield measurement. Then, the representative wavenumber which exhibits state of materials is selected by local wavenumber filtering. Acoustic wavenumber spectroscopy proposed by Flynn excites by using single frequency PZT, unlike the pulsed laser excitation, and receives standing wave energy using the LDV, so no time delay is required. Also, the excitation using the single frequency amplifies the structure's energy, so the SNR greatly increases without repetition measurement, compared to the pulsed laser method. Also, since the changes of the structure is measured by wavenumber, flat field according to the scan position is not needed to measure amplitude using LDV.

The method suggested by Flynn et. al. generates a wave pattern influenced by the propagation of the wave. So, the wavenumber of the sound area can be exaggerated as shown in the paper (E. B. Flynn, 2014), and wavenumber of sound edge is great difference from the actual state. These abnormal indication evaluates sound area of interrogated structures as damaged area. To overcome this problem, 2d FFT smoothing technique is proposed to remove a wave pattern influence and edge effect. Spatial local wavenumber filtering (SLWF) is carried out on the local wavenumber estimation result. Edge effect and wave pattern are reduced by using the spatial local wavenumber filtering method.

2. ACOUSTIC WAVENUMBER SPECTROSCOPY

The acoustic wavenumber spectroscopy using single frequency excitation was first introduced by Flynn [10]. Among many modes which are propagated by the induced ultrasonic wave, a single mode, which can best determine the defects, is selected, and a narrowband wavenumber filter, in which wavenumber changes, is used to select and visualize the largest wavenumber. There are six procedure to describe the acoustic wavenumber spectroscopy as follows as illustrated in Figure 2.

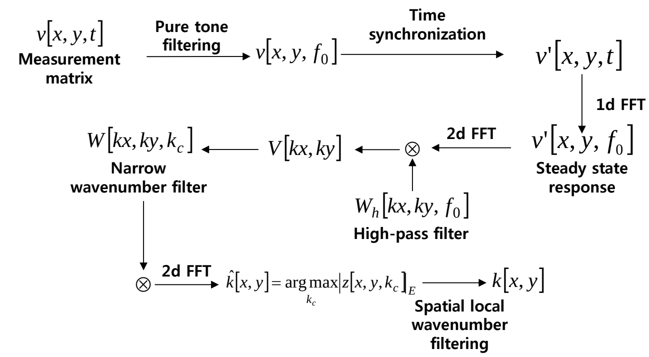


Figure 2. Flow diagram of spatial local wavenumber filtering

1) Pure tone filtering: Even though a PZT is excited by single tone sine wave, characteristics of power amplifier generates harmonic components. So, harmonic components are eliminated by digital bandpass filtering.

2) Time synchronization: Measured signals are synchronized with trigger of galvanometer in time domain. If it is not achieved in acquisition, this has to be done

3) Calculation of steady state response: Two dimensional steady state response is acquired by single frequency FFT using measured time history by following equation

$$v'[x,y,f_0]=\frac{1}{T}v[x,y,z]\exp[(-j(2\pi f)(t-\tau))] \quad (1)$$

4) Mode extraction: 2d high-pass filtering is adopted to extract anti-symmetric mode (A_0).

5) Generation of narrow wavenumber filter bank: To filter out unwanted wavenumber mode using narrow wavenumber filter bank

6) Calculation of maximum wavenumber, $\hat{k}[x,y]$ in spatial domain of $z[x,y,k_c]$

3. SPATIAL LOCAL WAVENUMBER FILTERING

The wavenumber calculation method as suggested by Flynn, is the method for calculating the wavenumber of the entire inspection area. However, the edge effect, which displays even the sound area as defects due to miscalculations, can occur, as shown in Figure 3. In the acoustic wavenumber spectroscopy, after passing through the narrowband wavenumber filtering, a wavenumber which makes the largest, is searched. The edge effect or wave pattern caused by passing through the narrowband wavenumber filter is generated, so the error from the actual wavenumber is enlarged. To decrease the error, the spatial local wavenumber filtering method is introduced to minimize and smoothen the original signal without distortion in this study. Within the spatial local area, 2D FFT is conducted to select the largest value as the representative wavenumber of the area. This is applied to the entire inspected area (See Figure 4). Whole procedure of spatial local wavenumber filtering is follows:

1) Extract data of local area from $\hat{k}[x,y]$. Length of m is twice of wavelength.

2) Perform 2D-FFT, and select largest value of 2D-FFT in the local area

3) Repeat the 1 and 2 in all local area, and obtain the $k[x,y]$.

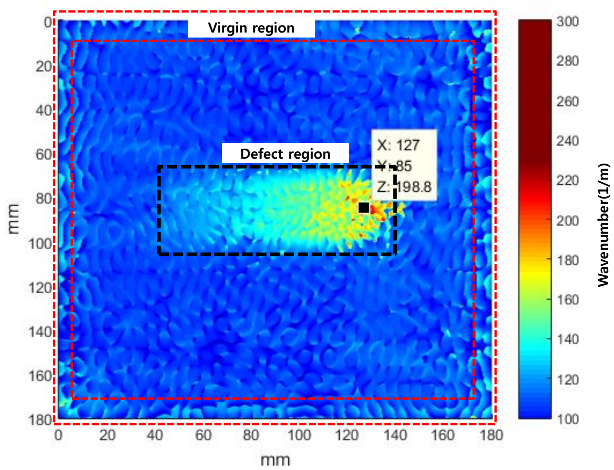


Figure 3. Damage visualization using narrow wavenumber filtering

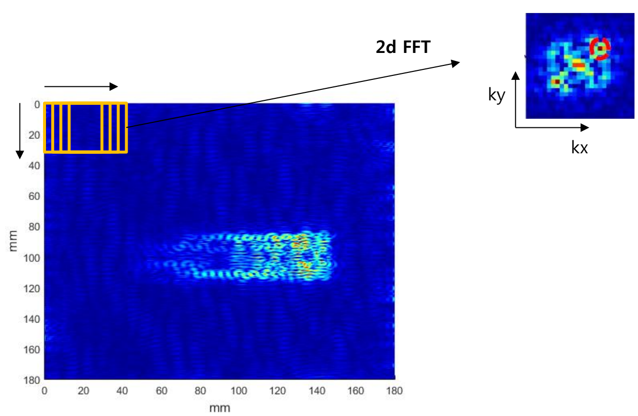


Figure 4. Method of spatial local wavenumber filtering

4. EXPERIMENT

4.1. Equipment and specimen

The equipment for experiment is as shown in Figure 5. Function generator for generating single frequency, amplifier for high-voltage amplification, PZT for excitation, mirror for scanning the area, vibrometer for receiving laser, and DAQ for collecting signals. To verify the spatial local wavenumber filtering method, a defect, in which the thickness changes from 0.5mm to 2.5mm, was inserted to an aluminum plate with 3mm thickness, 30mm (width) X 100mm (height), as shown in Figure 6.

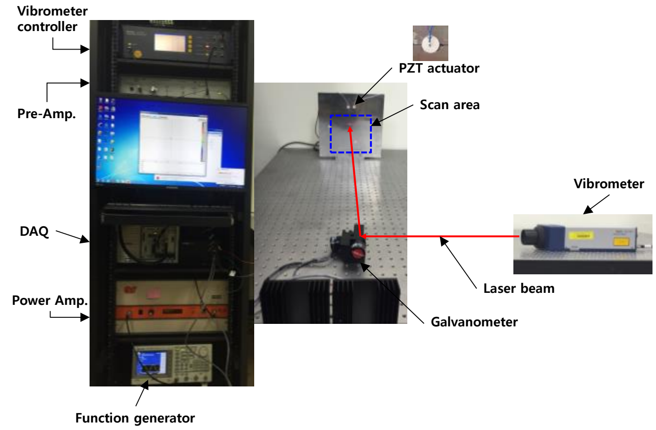


Figure 5. Experimental setup for laser scanning of plate structure

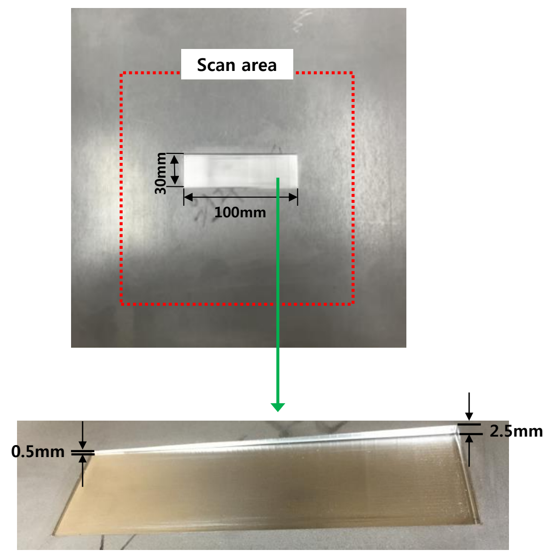
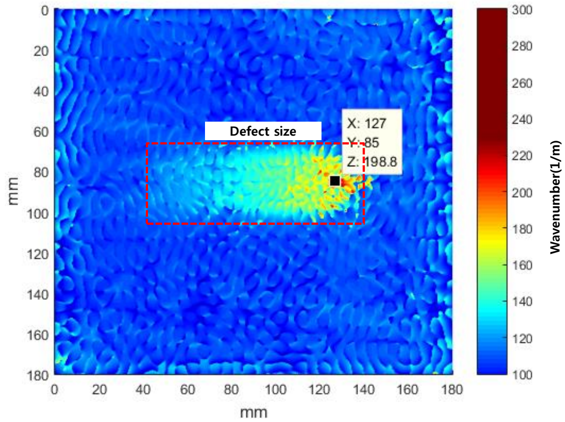


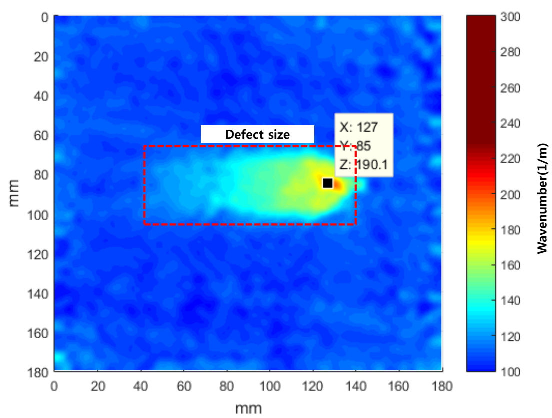
Figure 6. Defect configuration in alumium

4.2. Results and discussions

Figure 7 (a) shows the result obtained from the acoustic wavenumber spectroscopy. It can be found that the wavenumber of the edge is increasing. However, when applying the spatial local wavenumber filtering, the phenomenon of high wavenumber dissipated, unlike Figure 10 (a) as shown in Figure 7 (b). Instead, the wavenumber on the sound area on the edge is greatly improved. Although the difference between the spatial local wavenumber filtering and the acoustic wavenumber spectroscopy is about 4.4%, the image of the defect’s boundary becomes clear, and the abnormal signal on the edge without defect decreases.



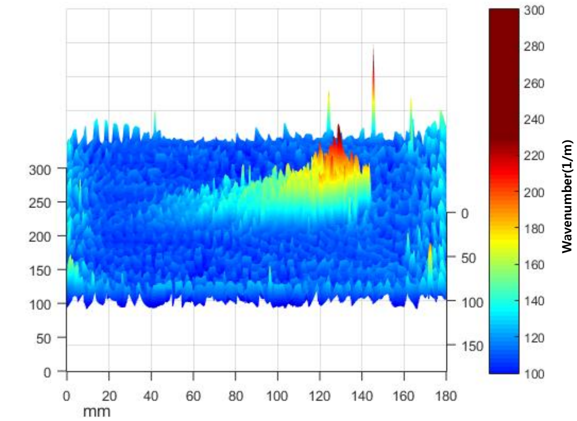
(a)



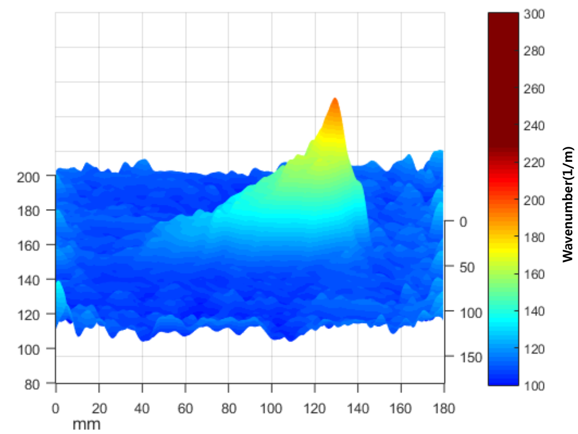
(b)

Figure 7. Wavenumber of a wall-thinned plate that has a linear thickness variation in aluminum (Azimuth: 0°, Elevation: 0°), (a) a result of acoustic wavenumber spectroscopy (b) a result of spatial local wavenumber filtering

Figure 8 shows the image of Figure 7, looked from the 32 degrees angle of altitude. Despite the soundness of the edge, the wavenumbers are exaggerated. Figure 8 (a) indicates that the wavenumbers on the edge are consistent and small, in comparison with Figure 8. The wavenumber of mode calculated by dispersion guidance on the 3mm-thick plate (sound part) is 99.4m^{-1}. The wavenumbers at which the error of the sound part becomes maximum were calculated and compared, resulting in the error of 159.6m^{-1} when calculated by the acoustic wavenumber spectroscopy, and as 23.5m^{-1} by the spatial local wavenumber filtering method. Thereby, the maximum error decreases from 160.6% to 9.1%.



(a)



(b)

Figure 8. Wavenumber of a wall-thinned plate that has a linear thickness variation in aluminum (Azimuth: 0°, Elevation: 32°) (a) a result of acoustic wavenumber spectroscopy (b) a result of spatial local wavenumber filtering

5. CONCLUSION

In this study, an aluminum plate, which was inserted with a defect of changing depth, was visualized by using the spatial local wavenumber filtering method. The shortcomings of the existing acoustic wavenumber spectroscopy, in which the wavenumbers on the edge are incorrectly calculated, have been overcome by applying the spatial local wavenumber filtering method. The method suggested in this study will be used for the measurement of plate's thickness, and wall thinning inspection in the future.

ACKNOWLEDGEMENT

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BIOGRAPHIES

To Kang received his B.S., M.S., and Ph.D. degrees in mechanical engineering from Sungkyunkwan University, Korea, in 2008, 2010, and 2017, respectively. From 2013 to 2016 he was researcher at the Korea Atomic Energy Research Institute. Since 2016, he has been a senior researcher of the Korea Atomic Energy Research Institute working in the fields of condition monitoring & diagnosis of mechanical system, ultrasonic nondestructive evaluation, and advanced signal processing technique for condition monitoring &diagnosis of mechanical system.