DAMAGE DETECTION ON THIN WALLED STRUCTURES WITH SINGLE FREQUENCY EXCITATION AND WAVENUMBER FILTERING
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Key words: Scanning Laser Doppler Vibrometry, Wavenumber filtering, Damage detection, Wave propagations

Abstract
This paper describes the use of wavenumber filtering for damage detection with a single-frequency standing wave excitation on thin plate structures. Using a single, fixed frequency excitation from a mounted piezoelectric transducer, the full standing wave-field could be obtained using a Laser Doppler Vibrometer (LDV) with a mirror tilting device. After scanning, a wavenumber filtering is performed to determine certain wavenumber components, which could be used for damage detection. Mapping processes based on local wavenumber filtering is then carried out for damaged area visualization. Also introduced are the comparison of two methods for damage identification and visualization: the local wavenumber mapping and acoustic wavenumber spectroscopy. To demonstrate the proposed techniques, several experiments are performed on thin walled structures with several different types of damage, including corrosion in an aluminum plate and debonding on composite plates. The results demonstrate that the techniques are very effective in localizing damage with the potential for the improved damage detection capabilities with a high interrogation speed.

1 INTRODUCTION

Thin-walled components are widely used in many engineering applications, including vehicles, buildings, plants, and aerospace structures. Invisible damage such as corrosion and erosion could happen to these components, which requires the implementation of structural health monitoring (SHM) or nondestructive evaluation (NDE) techniques to detect structural damage. [1, 2]. There are several NDE techniques to detect damage, including radiography testing [3], magnetic particles testing [4], eddy current testing [5] and many others. These methods usually require various precautions and lengthy inspection.

Techniques based on ultrasonic waves such as acoustic and Lamb waves have been extensively studied for damage detection because they are able to propagate a long distance and are sensitive to small defects in a structure. Among other techniques based on wave propagations, several techniques are emerged to capitalize on the full field of ultrasonic wave imaging for damage detection and visualization. Lee et al., [6] developed a unique system, referred to as UPI (Ultrasonic Propagation Imaging), where a Q-switched laser pulse was utilized to excite a surface of structures and an embedded sensor was used to measure
subsequent propagated waves. After using several signal processing tools, various types of damages (corrosion, cracks, debonding, etc) could be identified with damage-induced reflected and scattering waves. In their studies, a time of flight mapping technique was applied for the wall thinning pipe to visualize damage in the form of ToF map. [7]. The UPI system has also applied to several structures, including crack detection in a welded pipe [8], and composite aircraft structures [9].

Guided wave propagation patterns are complicated and difficult to analyze due to their dispersive and multimodal behaviors. Hence, most guided wave field damage detection requires to simplify to separate a single wave mode. This separation could be accomplished based on wavenumber analysis. Rogge et al. [10] used a laser Doppler vibrometer to measure wave field data for composites and showed that the estimation of local wavenumber can lead to effective and quantitative evaluation of the size and the depth of delamination in composite plates. Mesnil et al. [11] applied both instantaneous and local wavenumber damage quantification techniques to guided wave field data and compared in terms of accuracy in damage characterization. Ruzzene et al. [12, 13] to separate propagating, converted, and reflected modes, which are often required to analyze multimode guided wave field. Kudela et al. [14] showed that wavenumber filtering is an effective tool for evaluating a crack in thin walled structures.

Recently, the use of standing waves, instead of using traveling waves as in the previous studies, was proposed [15, 16]. This method uses a single, fixed frequency excitation and provides the following advantages [16].

1. Energy is effectively “pumped” into structures, resulting in the higher magnitude of waves.
2. The delay time to wait until previous waves completely die out is not required for continuous measurements.
3. Only a few cycles of wave measurements are sufficient to capture the wave behaviors at each scanning point.

Based on these studies, our study begins to effectively visualize damage on various plate structures using the standing wave analysis. We developed a scanning system consists of Laser Doppler vibrometer (LDV) and a mirror tilting system to measure full wave field. A piezo transducer is embedded on a structure to provide an excitation at a single frequency. After the scanning process completed, the measured signals are rearranged to generate full wave field in the steady state. In order to detect and visualize damaged area, signal processing tools, including LWM (Local Wavenumber Mapping) and AWS (Acoustic Wavenumber Spectroscopy), are implemented and their performances are compared. Several experiments with aluminum plates, pipes and CFRP plates are conducted for validation of the proposed methods.
2 MEASUREMENTS APPROACH

A laser scanning system for full wave field measurements consists of following components which are 1) Piezo transducer for a single, ultrasonic actuation, 2) Data acquisition device to generate an ultrasonic wave and to measure subsequent structural responses, 3) Laser Doppler Vibrometer, 4) A mirror-tilting system to control the position of laser sensing points and 5) A signal processor. A piezo transducer is attached on the surface of a plate and generates a standing wave at high frequency (> 50 kHz). Because of standing wave excitations, a structure experiences the steady state responses, which are measured in the size of T x N x M by the system. T is the time data of each sensing point, and N and M are the number of spatial points in the x and y directions. The excitation frequency is normally set at higher than 80 kHz with the sampling frequency of 1MHz. Once structural responses are measured, the steady-state response, \( r(x, y) \) of the excitation frequency is extracted by applying Discrete Fourier Transform. Because a steady-state response at the excitation frequency eliminates other frequency components, high signal to noise ratio could be obtained.

\[
r(x, y) = \frac{1}{T} \sum_{t=0}^{T} v[x, y, t] \exp(-j2\pi ft)
\] 

(1)
3. DAMAGE VISUALIZATION BASED ON WAVENUMBER

3.1 ACOUSTIC WAVENUMBER SPECTROSCOPY

Acoustic wavenumber spectroscopy starts from the extracted response function. This technique was developed by Flynn et al. [16]. As shown in figure 2, the response function has steady-state response of the wave field. A wavelength will be changed if there is a structural thickness and/or material property variation. Therefore, if damage present in a certain area of structures, the wavelength will be modified in that specific area, which is the base of this technique. First, the wave field domain is converted to wavenumber domain by conducting 2D FFT. The filter bank is then generated by gradually increasing radius of torus with a certain width in the wavenumber domain, where the radius, $k_c$, corresponds to the dominant wavenumber in a filter bank. Each wavenumber component is extracted after the measurement matrix passes through the generated wavenumber filter bank. As the next step, each extracted result is reconstructed and spatial envelope is calculated. Finally damage is visualized by searching a certain wavenumber that maximizes amplitude of the spatial envelope.

3.2 LOCAL WAVENUMBER MAPPING

The procedure of damage identification and visualization of LWM also starts from the same response function which is used in AWS. In this technique, the dominant wavenumbers of a local window are extracted and mapped to entire surface to find out damaged area. First, a partial wave field in a local window is extracted and converted to the wavenumber domain. In
order to reduce the magnitude of side lobes in the wavenumber domain, a hanning window is applied to the extracted wave field. The dominant wavenumber is identified after performing 2D FFT, and finally, the estimated wavenumber is mapped at every window position for damage visualization.

4. EXPERIMENT RESULTS AND DISCUSSION

In this section, several damage visualization results are presented from several structures. The test structures include an aluminum plate, a steel pipe with corrosion damage, and CFRP with the debonding damage between two plates.

4.1 ALUMINUM PLATE

The experiment was performed with an aluminum plate with $900 \times 900 \times 4$ mm. As depicted in figure 4(a), corrosion damage, with the approximate size of 50 mm diameter, was introduced to one side of the surface. The excitation frequency was set as 100 kHz and the measurements were taken in the area of $200 \times 200$ mm at the spatial resolution of 1 mm. Figure 4(b) shows the steady-state wave field on the aluminum plate. Although it shows change in the wave pattern due to the corrosion, it is not easily distinguished by the response image. Figure 5 shows the damage detection result using LWM and AWS techniques, respectively. Both techniques could detect the corrosion damage with similar accuracy. It shows the same trend that as the corrosion depth becomes larger, there are corresponding changes in wavenumbers.

![Figure 4: Picture of corrosion mark on hidden surface and steady-state response](image-url)
4.2 STEEL PIPE

As a second experiment, a steel pipe, with 140mm radius and 6mm thickness was used. On the inner curved surface of the pipe, PWSCC (Primary Water Stress Corrosion Crack) damage was introduced, which usually caused by continuous and pressurized flows. As depicted in figure 6, the PWSCC has a 70 x 70mm of area, with the maximum thinned depth of the 50% of the pipe’s thickness. The excitation frequency was set as 80kHz, and the outer surface of 130 x 200mm was scanned with a 0.5mm of spatial resolution. As shown in figure 7(a), the wavelength was kept in consistent value on the undamaged area but there are significant changes at the damaged area. The same techniques, LWM and AWS, were also applied to the measured wave field. Both methods are able to identify the damaged area correctly, with the pronounced changes in wavenumber at the corrosion depth is increased.
4.3 CFRP PLATES

This experiment includes the debonding detection in two jointed CFRP plates. The composite plates (2mm thickness) were bonded each other (120 × 55mm), except the area (40 × 55mm), as shown in figure 8(a). The same procedure was used as in the previous experiment. Because the CFRP plate’s high damping characteristics, reflected and scattering
waves were barely observed on the surface of the CFRP plate as shown in figure 8(b). The boundary surface can be found as the difference between the amplitude. However, the bonding and debonding areas are not easily distinguished by the response. By using LWM and AWS, the debonding area was relatively well identified, although it is not as obvious as in the previous cases.

Figure 8: Picture of CFRP with debonding and steady-state response

Figure 9: (a) LWM, (b) AWS. CFRP with debonding
5. CONCLUSION

The damage detection technique, which utilizes a steady state wave field data acquired by scanning LDV, is developed and tested. Two signal processing methods are also implemented, including acoustic wavenumber spectroscopy and local wavenumber mapping. The proposed technique has following advantages: 1) Signals with high SNR could be achieved because energy is effectively pumped into structures, 2) It does not require synchronization between excitation and measurement, 3) A few data are enough to capture wave’s behavior and 4) Robust damage visualization is possible by utilizing wavenumber feature. For validation of the proposed technique, several experiments were conducted with an aluminum plate, a curved steel pipe and CFRP plates. Experiments results show that structural damage was clearly and accurately identified. These results prove that the use of standing wave for laser scanning system is very effective to evaluate several types of damage on several types of structure. Suggestion of further work is to further enhancing the sensitivity of the method to much smaller defects in a structure.

6. ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education (NRF-2015R1D1A1A01059092) and by the Ministry of Science, ICT and Future planning (2015-0707)

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