Fast Inversion Calculation for Full-field Measurement of Material Properties with Quantitative Laser Ultrasound Visualization System

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Abstract.
This research employs a nondestructive, rapid, high accuracy and full-field material characterization platform which integrates quantitative laser ultrasound visualization system (QLUVS) with mechanical property mapping reconstruction algorithm. The QLUVS uses a pulsed laser generate acoustic waves with fast scanning mechanical to research two dimensional scanning goal and then detected with a piezoelectric longitudinal transducer. By utilizing QLUVS, the spatial and temporal information of guided wave can be obtained with further signal processing. The theoretical models including guided waves propagating along single-layered plate, two-layered plate, surface wave for single-layered system and for two-layered system and signal processing including 2D spatial data interpolation, window shifting and 2D fast Fourier transform (2D FFT) will be integrated into mechanical property mapping reconstruction algorithm.

The QLUV system combined with mechanical property mapping reconstruction algorithm provides qualitative and quantitative study for more complex guided mode propagating behavior and a full-field mechanical property mapping.

1. Introduction

In previous research, the propagation phenomena of guided wave, like as Lamb wave can only be investigated by theoretical model or finite-element method (FEM). In recent decades, the guided wave propagating phenomenon is studied and applied widely by experimental method. Ultrasound tomography is an inspected method based on the wave propagating behavior [1]. It can allow large region of structure to be rapidly inspected. However there are some assumptions needs to revised wave propagation phenomena. Some research use wave propagating behavior to capture the defect in the structure. However they just investigated quantitative of defect [2-5]. Some research use same technique to investigate quantitative results regarding to dispersive Lamb waves. However it just does quantitative evaluation for local area [6].

Laser ultrasound generation [7] is a kind of ultrasound (UT) technique which employs the absorption and liberation remotely to generate wide bandwidth, point-wise, and nondestructive ultrasound with a high energy pulsed laser in order to apply the measurement without environment effect. The ultrasound based technique, via generating with a pulsed laser and detecting with a transducer, quantitative laser ultrasound visualization (QLUV) system is developed. The QLUV system employs the pulsed laser to scan over the interested
area on the surface of an arbitrary shape of material then detects with a piezoelectric transducer. With the aid of reciprocal theorem, dynamic behaviors of wave propagation can be reconstructed.

Further this research develops a novel algorithm called mechanical property mapping reconstruction algorithm, including spatial data interpolation method and database inversion method based on QLUVS to obtain the full-field mechanical property.

2. Methodology

2.1 Spatial data interpolation method

Utilizing QLUVS system, the wave propagating phenomenon at any time slice at specific position can be obtained. Further for the purpose of extracting information in arbitrary position from QLUVS experimental data, the spatial data interpolation must be utilized. Such as Fig. 1, the resolved wavefronts of guided wave could be obtained by using QLUVS. Spatial data interpolation is employed to extract the absolute amplitude for desired point at specific time, such as Fig. 2. Here the cubic spline interpolation is utilized to interpolate the information of desired point. In the Fig. 2, the ε is set as a convergence condition. When the distance between interpolation and desired point is less than ε, then the interpolation point and desired point have same information. Further using spatial interpolation method for the resolved wavefronts at different time, the absolute amplitude information can be interpolated at desired point at different time.

Fig. 1. The resolved wavefronts by QLUV system.

Fig. 2. Spatial interpolation method.
2.2 Database inversion method

For this research, Golden-section and Simplex optimum method are applied to obtain the material property. However for a full-field case by QLUVS, there are a very large number of dispersion curve for processing. Therefore building dispersion database is very suitable for full-field inversion. For different case, the dispersion curve is stored in the database. Then Golden-section and Simplex method is employed to search optimum material property from dispersion database for measured specimen. In this research, the Lamb wave, surface wave and multi-layer surface wave is added in database for inversion purpose.

3. Experiment

3.1 Specimen

Fig. 3 shows the specimen in this research. Table 1 is specimen description. Four cases are used to highlight the QLUVS and mechanical property mapping reconstruction algorithm. There are aluminum plate, aluminum plate with two defects, aluminum block with temperature gradient and thermal spray material. It is shown in Fig. 3 individually.

![Specimen](image)

**TABLE 1**

<table>
<thead>
<tr>
<th>Notation</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>Al</td>
<td>Al</td>
<td>Al</td>
<td>Ni-Al(coating) / Steel (substrate)</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 (mm)</td>
<td>Block</td>
<td>Coating material</td>
<td></td>
</tr>
<tr>
<td>Condition</td>
<td>No defect</td>
<td>One circular thinning</td>
<td>Heating</td>
<td></td>
</tr>
<tr>
<td>Coating thickness</td>
<td>1000-2000 (μm)</td>
<td>100X100 (mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scanning area (QLUV)</td>
<td>50X50 (mm²)</td>
<td>50X16 (mm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variables inversion</td>
<td>E, v and h</td>
<td>h</td>
<td>E</td>
<td>E</td>
</tr>
</tbody>
</table>
A quantitative laser ultrasound visualization system (QLUVS) is used for the visualization of Lamb wave modes propagation along the plate. Fig. 4 shows a schematic for the experimental configuration of the QLUVS. The QLUVS includes a pulsed Nd:YAG laser, a longitudinal transducer, a pulser-receiver, a fast rotational scanning stage, and a computer with fast A/D converter. The pulsed Nd:YAG laser with a wavelength of 1064 nm, an energy of about 10 mJ, and 0.7 mm beam diameter is used for the generation of ultrasonic acoustic waves propagating in the plate. The pulsed laser has a maximum repetition rate is up to 20 KHz. The receiver and 5 MHz longitudinal transducer are utilized to detect ultrasound. The scanning stage is a two axial rotational servo motor and controlled by the computer which drives two mirrors to scan the Nd:YAG laser beam on the surface area of plate. The computer with a fast A/D converter is used for controlling the scanning stage.

With the QLUV system, the step 1 is an ultrasonic signal can be generated with the pulsed laser at a desired position located on a scanning plane indicated in Fig. 4. It is defined origin position. The generated ultrasonic waves are then detected with the longitudinal transducer. The step 2 is the pulsed laser is scanned along axial and the detected signals pile up into a data cube with the dimensions of (X,Y, t) in the same direction. And then in step 3, the information is collected and pile up into a data cube in different direction (X,Y, t).

While the data cube is time-gated at various elapsed times, a series of pictures are created. With the aid of reciprocal theorem, such as Fig. 5, these pictures represent many instantaneous frames representing wavefronts generated by the longitudinal transducer and detected at the scanning area. In this way, the QLUV system is operated.
4. Results and discussions

4.1 Aluminum with no defect

Fig. 6 shows the QLUVS resolved wavefronts for aluminum plate specimen. Through Fig. 6, it exists multi-mode. And there are not deformed wave in this resolved wavefronts. According to this result, there are no defects in this case. Further, mechanical property mapping reconstruction algorithm is employed to extract material property, shown in following three figure. The Fig. 7, Fig. 8 and Fig. 9 represent Young’s modulus map, Poisson’s ratio map and thickness map. From these results, the aluminum plate has very uniform material property.

Fig. 6. The resolved wavefronts of Lamb wave of aluminum plate by QLUV system.

Fig. 7. Young’s map for aluminum plate.

Fig. 8. Poisson’s ratio map for aluminum plate.
4.2 Aluminum with no defect

For aluminum with two defects, Fig. 10 shows the resolved wavefronts. According to these results, reflected wave and scattered wave can be observed obviously. Fig. 11 illustrates the application of our algorithm to the thickness inversion of QLUVS data acquired on 1mm thick aluminum plate with two machined defect. Utilizing the mechanical property mapping reconstruction algorithm, the thickness mapping can be reconstructed. It is shown thickness variation obviously. Fig. 11 represents the top view for this case.
4.3 Aluminum block with temperature gradient

For this case, the aluminum block is heated with different heat source in different position shown in Fig. 1 (C). When specimen is heated, the direct influence is Young’s modulus variation. From this case, the relationship between temperature and Young’s modulus must be established. Fig. 12 and Fig. 13 show the Young’s modulus and temperature map. Young’s modulus and temperature variation are observed obviously.

![Fig. 12. Young’s modulus map for aluminum block with temperature gradient.](image)

![Fig. 13. Temperature map for aluminum block with temperature gradient.](image)

4.4 Thermal spray material (Ni-Al/steel)

Fig. 14 shows the Young’s modulus map for thermal spray material. From this result, it is easily illustrated that when thickness of coating material thicker, Young’s modulus will increase.

![Fig. 14. Young’s modulus map for thickness variation of thermal spray processing.](image)
5. Conclusions

In this research, quantitative laser ultrasound visualization system (QLUV) is employed for the investigation of Lamb wave modes propagating in aluminum plate, aluminum plate with two defects, aluminum block with temperature gradient and thermal spray material. With the QLUV system, continuous dynamic propagation behaviors of the Lamb wave modes interacting with the different material properties are observed.

Utilizing the development of the full-field mechanical property inspection technology, full-field mechanical property measured by non-destructive, high-speed and high-precision measurements can be obtained in qualitative and quantitative results.

Acknowledgements

Financial support from Ministry of Science and Technology, Taiwan, through grant No. 104-2221-E-027-001- is gratefully acknowledged.

References