Guided Wave Testing for Structural Component by Multipoint Sensing with Wireless Accelerometers

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Abstract. When a guided wave is applied to a structural component in civil infrastructure, it is important to note the dimensions of the cross-section and the heterogeneity of the components. In this study, we proposed a wireless measurement system to measure the guided wave in the kHz frequency range. The guided wave was excited with an impact hammer. It was then received with wireless accelerometers at plural points. In order to enhance the accuracy of the guided wave testing, the propagation mode representing wave packets with different wave velocities is required. A semi-analytical finite element method was utilized to obtain the dispersion curve of the propagation mode. The numerically calculated and the measured dispersion curves showed good agreement for the I-beam metal specimen. The wave components with zero group velocity were observed in the measured dispersion curve. Investigations revealed that the components were caused by a natural vibration mode.

1. Introduction

Guided waves are applied to a wide variety of non-destructive tests including plate, bar, and pipe tests [1]. Ultrasonic guided wave modes propagating over long distances are useful in rapid inspection. When the guided wave is applied to structural components in civil infrastructure, the dimension of the cross-section and the heterogeneity of the components pose problems. This prevents us from utilizing an ultrasonic wave in a high frequency range. Furthermore, using a transducer to generate an ultrasonic wave with a specific frequency range is not optimal as there are differences in the shape and size of the waves in each infrastructure. Hence, a portable measurement device is required for on-site inspection. However, using the advanced hardware technology of smart sensors with wireless data communication can solve this problem [2]. In this study, we propose a wireless measurement system to measure the guided wave and visualize its propagation. The guided wave is excited with an impact hammer, and then received with accelerometers at plural points. The accelerometer is utilized due to its wide frequency band.

Fundamental information on the propagation mode and wave dispersion relation is required at the time of inspection in order to enhance the accuracy and reliability of the guided wave testing. Specifically, the structural component of bridges shows a complicated geometry in the cross-section. Hence, a semi-analytical finite element (SAFE) method was utilized [3, 4]. In this method, wave motions in the propagation direction were treated theoretically and the cross-section was sub-divided. The wireless measurement system is
validated with an accelerometer for the guided wave testing by using an aluminum I-beam specimen. First, the propagation of the guided wave in the I-beam is visualized. Subsequently, the measured dispersion curve is compared with the dispersion curve, which is numerically calculated via SAFE. We also illustrate the appearance of the natural vibration mode caused by the guided wave propagation.

2. Wireless Measurement System of Guided Wave

2.1 Hardware Configuration

The measurement system of the guided wave was composed of a wireless sensor node, a wireless router, and a personal computer (PC) at the base station. Two wireless sensor nodes were mounted. One of the wireless sensor nodes had an impact hammer (Fuji Ceramics, FHA2KC) to generate a shock wave into the target. The other wireless sensor nodes received the guided wave by using a piezoelectric accelerometer (Fuji Ceramics, SA11ZSCA, Frequency response: 0.5–15 kHz, Voltage sensitivity: 1.0 mV/m/s², measurement range: 5000 m/s², and weight: 4.4g), which measures the acceleration along the three axes. The voltage signal is transformed into digital data by using an analog-to-digital converter (WLS-9215 by National Instruments). The digital data is sent to the PC at the base station through a wireless router. In the case when the acceleration was measured in three directional axes at a sampling rate of 100 kHz, a router with a transfer speed exceeding 4.8 Mbps (=100 k × 16 bit × 3 axes) was necessary. The nominal transfer speed of a wireless router with IEEE802.11g standard is 54 Mbps. Hence, approximately 11 nodes could be logically linked. The time synchronization of each sensor node was important and it was accurately determined by using the pulse per second (PPS) signal sent from the global positioning system (GPS) sensor through the GPS signal-receiving sensor (Navisys Technology, GM-316). The PPS signal error was less than 1 μs. By using the time synchronization, data with a sampling rate of 100 kHz was accurately obtained.

Fig. 1. The guided wave measurement system comprised of a hammer sensor node, receiving sensor nodes, a wireless LAN router, and a mobile laptop.

2.2 Software Control

The graphical programming environment of LabVIEW (National Instruments) was used to develop the software to control all sensor nodes, collect data, and conduct waveform processing. In this system, the 3D deformation caused by wave propagation could be visualized. We used the following linear acceleration method [5] to transform the acceleration given by the sensor into the displacement. We express \( \Delta t \) as the sampling
interval. The velocity $v^n = (v^n_x, v^n_y, v^n_z)$ of the integer step $n$ is calculated from accelerations $a^{n-1}$ and $a^n$ as follows:

$$
v^n_i = v^{n-1}_i + \Delta t \left( \frac{a^{n-1}_i + a^n_i}{2} \right), \quad i = x, y, z
$$

(1)

Similarly, the displacement $u^n$ can be obtained as follows:

$$
u^n_i = u^{n-1}_i + \Delta t v^{n-1}_i + \Delta t^2 \left( \frac{a^{n-1}_i + a^n_i}{3} \right), \quad i = x, y, z
$$

(2)

where $v^0 = \emptyset$ and $u^0 = \emptyset$. At times, a baseline deviation associated with displacement occurs when the numerical integration is performed. This is known as the drift error of the displacement, and it can be corrected with a digital filter. A high-pass digital filter was designed to remove only the low frequencies associated with the drift error. We displayed the 3D animation of the wave propagation in the structural components by mapping the displacement information of each point on CAD. In order to visualize the deformation smoothly, the interspatial displacements between sensor nodes were interpolated using the spline function.

2. Semi-analytical Finite Element Method

A SAFE method for waveguides of arbitrary cross-section was demonstrated in [3] and [4] for a non-destructive testing application. The general SAFE approach utilizes a finite element discretization of the cross-section of the target material. The displacements along the wave propagation direction are described in an analytical fashion as harmonic exponential functions. Thus, only a two-dimensional discretization of the cross-section leads to considerable computational savings when compared to a 3D discretization of the entire waveguide. The following paragraph describes the outline of the SAFE.

We assumed that the wave propagated along the $z$ direction with wavenumber $\xi$ and frequency $\omega$. The $x$-$y$ plane contained the cross-section. The displacement field was assumed to be harmonic along the propagation direction, $z$, and a spatial function was used to describe the magnitude in the cross-sectional plane. The cross-sectional domain of the waveguide can be represented by a system of finite elements. The discretized form of the displacement over the element $(e)$ could be written in terms of the shape function, $N_i(y, z)$, and the unknown nodal displacements $u^e_i$ as follows:

$$
u(e)(x, y, z, t) = \sum_{k=1}^{n} N_k(x, y) U^e_k \exp(i(\xi z - \omega t)) = N(x, y) q^e \exp(i(\xi z - \omega t))
$$

(3)

where $N$ is the matrix of the shape function $N_i$, $q^e$ is the vector of nodal displacement, $n$ is the number of nodes per element, and $i = \sqrt{-1}$ is the imaginary unit. The virtual work principle gives the following governing equations:

$$
\int_{t_1}^{t_2} \left\{ \int_{\Omega(e)} [\partial U^e \cdot \nabla V + \int_{\Gamma_{\text{int}}(e)} \rho (U^e) \cdot \nabla \mathbf{V}] \right\} \, dt = 0
$$

(4)

where $\partial$ is the differential operator matrix, $*$ denotes the complex conjugate, $\tau$ is the stress vector, $\rho$ is the density, $L$ is the total number of element, and $\dot{u} = \partial^2 u / \partial t^2$. 

3
Finally, the above equation results in a form of an eigenvalue problem as follows:

$$[A - \xi B]_{2M} Q = 0$$  

(5)

where $A$ and $B$ are symmetric matrices [3]. From Eq. (5), $2M$ eigenvalues $\xi_m$ and corresponding eigenvectors are obtained at each frequency $\omega$ ($M$ is three times the number of nodes). Phase velocity of the $m$-th mode is given by $\left(c_p\right)_m = \omega / \xi_m$. These eigenvalues consist of wavenumbers for both $M$ forward waves and $M$ backward waves. When $\xi_m$ is a complex number, the $m$-th mode is an evanescent mode. For real $\xi_m$, the $m$-th mode is a propagating mode.

3. Visualization of Guided Wave in I-beam Metal

3.1 I-beam Aluminium Specimen and Sensor Position

Experimental measurements were used to check the measurement system. As shown in Fig. 2(a), the measurement target is an aluminum I-beam (longitudinal wave velocity: 6360 m/s, transverse wave velocity: 3040 m/s, density: 2700 kg/m$^3$). The cross-sectional, vertical, and longitudinal axis are expressed as the $x$, $y$, and $z$ directions, respectively. The specimen is simply-supported at both ends. Figure 2(b) shows the positions of the wireless sensor nodes. The receiving sensors are located on the upper and lower flanges and at the side of the web. Eight measuring lines (ML.1 to ML.8) were also set. On each line, the guided wave is measured at 100 locations at intervals of 20 mm. To generate the guided wave in the specimen, the impact hammer was used on the upper flange in Fig. 2(b) to provide the impact.

![Fig. 2.](image)
measuring lines (MLs) 1 to 8.

3.2 Visualization of Guided Wave

Figure 3 depicts the 3D visualization result of the I-beam specimen using the displacement data obtained in ML.1 to ML.8. The CAD, sensor locations, and displacement data are fed into the visualization software (Advanced Visual Systems, AVS/Express Viz). The spatial spline interpolation method was used to interpolate the displacement data between sensor nodes. In Fig. 3, the color indicates the magnitude of the displacement, i.e., \( |\mathbf{u}| = \sqrt{u_x^2 + u_y^2 + u_z^2} \). The maximum value normalizes the magnitude. As the impact was given at the upper flange, a large deformation was observed in the upper flange. However, the guided wave propagated in the upper flange, as well as in the lower flange and the web.

![Figure 3. Visualization result of guided wave propagation.](image)

4. Dispersion Curves for I-beam Metal

4.1 Dispersion Curve

Two dimensional discrete data in the time direction and in the spatial direction (sensor position) were converted into data in the frequency domain \( f \) and in the wave number domain \( k \), respectively. The following two dimensional Fourier transform was used:

\[
H(k, f) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} a_i(z, t) \exp \{i(kz - \omega t)\} \, dz \, dt
\]

Figure 4 shows the experimental and calculated dispersion curves by the SAFE with 400 elements. In Fig. 4, the black dot denotes the calculated value. The color illustrations in Fig. 4(a) and (c) show the dispersion curves made by the acceleration \( a_y \) on the ML.2 and ML.5, respectively. Conversely, Fig. 4(b) shows the dispersion curves made by the acceleration \( a_x \) on the ML.4. Here \( H \) is normalized by the maximum data at each frequency. These results indicated that the black dots agreed well with the experimental results. However, the color illustrations in ML.2, 4, and 5 show different dispersion curves. It was found that all curves obtained in the SAFE calculation did not appear in the experimental dispersion curves. The
appearance of the dispersion curve depends on the position and the manner in which the impact was excited. Furthermore, different curves may appear by using the acceleration data measured in the other direction.

4.2 Characteristics of Zero Group Velocity

In Fig. 4, a few horizontal lines could be observed in the experimental data. For example, the component in the frequency at approximately 1306 Hz in Fig. 4(a) is significant. Since the slope angle of the dispersion curve indicates the group velocity \( c_g = \frac{\partial \omega}{\partial k} \), the horizontal line expresses the zero group velocity. However, this component is absent in the numerical dispersion curve. Hence, this phenomena could be caused by the vibration of the I-beam specimen. The 3D modal analysis was performed by using a finite element method software (NX Nastran). Figure 5(a) shows the result of the modal analysis. Figure 5(b) illustrates a snapshot of the guided wave animation in Fig. 3 after a band-pass filter of narrowband (1280–1330 Hz) was passed. Figure 5(c) exhibits the mode deformation in the \( y \) direction on the ML.1. The simulated and measured snapshots are in good agreement with the mode shape. We also demonstrated the appearance of the natural vibration mode caused by the guided wave propagation.

5. Conclusions

In this study, a wireless measurement system was proposed to measure the guided wave in
the kHz frequency range. The guided wave was excited with an impact hammer and then received with wireless accelerometers at plural points. To better understand the propagation mode and wave velocity, the SAFE method was utilized. The numerically calculated and measured dispersion curves showed good agreement for the I-beam metal specimen. In the measured dispersion curve, wave components with zero group velocity were observed. It was demonstrated that the components were caused by the natural vibration mode when the guided wave was propagating.

Future work will include the application of the measurement system to evaluate and detect flaws.

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References


