Guided Wave Generation and Sensing
Using a Single Laser Source and Optical Fibers

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Approved by
Professor Hoon Sohn

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ABSTRACT

This study proposes an integrated lead zirconate titanate/fiber Bragg grating (PZT/FBG) system that can generate and measure guided waves for structural health monitoring (SHM) using a common laser source and optical cables. Among various SHM devices used for guided wave generation and sensing, PZT transducers and FBG sensors have been widely used because of their light weight, non-intrusive nature and compactness. To take the best advantage of the merits of these SHM devices, a combination of PZT-based guided wave generation and FBG-based sensing has been attempted by some researchers. However, the existing hybrid approaches have two independent systems: a wave generation system using electrical devices and a sensing system with optical devices. We have developed a fully integrated PZT/FBG system that uses a single laser source and optical cables. This system can alleviate problems associated with conventional electrical cables, such as electromagnetic interference (EMI), signal attenuation, and vulnerability to noise. A tunable laser, the common power source for guided wave generation and sensing, is modulated and amplified to excite PZT transducers. This laser is also used with FBG sensors for measuring high-speed strain changes induced by guided waves. The feasibility of this system has been experimentally demonstrated in an experimental setup.
Keywords: guided waves, structural health monitoring (SHM), lead zirconate titanate (PZT) transducer, fiber Bragg grating (FBG) sensor, tunable laser source, optical fiber
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CHAPTER 1
INTRODUCTION

1.1 Motivation

In recent years, structural health monitoring (SHM) has become crucial for proper stewardship of critical infrastructure, high-capital mechanical systems and aging aircrafts (Sohn et al. 2004, Ansari 2005, Inman et al. 2005, Balageas et al. 2006, Adams 2007). Among various SHM approaches, techniques based on guided waves have gained popularity because these waves can propagate over a long distance and are sensitive to small defects (Victorov 1967, Giurgiutiu 2008). There is a rich volume of literature on SHM and damage detection techniques based on guided waves (Moulin et al. 1997, Yang et al. 1998, Kessler et al. 2002, Sohn et al. 2003, Raghavan et al. 2007).

Guided waves can be generated and sensed using various types of transducers including electro-magnetic acoustic transducers (EMAT) (Böttger et al. 1987, Gori et al. 1996), wedge transducers (Guo et al. 1994), and air/fluid-coupled transducers (Ke et al. 2009, Kim et al. 2009), and laser-based non-contact methods (Yamanaka et al. 1991, Halkon et al. 2006). Among various devices used for guided wave generation and sensing, piezoelectric lead zirconate titanate (PZT) transducers have been widely accepted because of their negligible mass/volume, cost-effectiveness, and non-intrusive nature (Measures 2001, Bass et al. 2002, Su
et al. 2006). There are a number of studies in which PZT transducers have been used for guided wave generation and sensing (Han et al. 1997, Shin et al. 1998, Tseng et al. 2002, Ihn et al. 2004, Kim et al. 2007). However, because PZT transducers require electrical cables, these transducers are susceptible to electromagnetic interference (EMI) that induces crosstalk during guided wave generation and sensing. On the other hand, fiber Bragg grating (FBG) sensors are mainly used for guided wave measurements. The advantages of FBG sensors include their light weight, long life and the ease with which they can be embedded into structures (Su et al. 2006). Furthermore, optical fibers are often used for a long-range signal transmission; these fibers are immune to EMI, less susceptible to noises, and attractive for space applications because they do not become spark sources that can be particularly dangerous near the fuel tanks of spacecraft. However, FBG sensors cannot be used for generating guided waves because of the passive natures of these sensors.
1.2 Research objectives

In order to take advantage of the strengths of both PZT transducers and FBG sensors, combinations of PZT-based guided wave actuation and FBG-based sensing have been attempted (Betz et al. 2003, Qing et al. 2005, Tsuda 2006, Komatsuzaki 2007). This hybrid PZT/FBG system is less vulnerable to EMI. Further, simultaneous measurements of guided waves at multiple points are possible because of the multiplexing capability of FBG sensors (Fernandez et al. 2001, Dai et al. 2009). However, the conventional hybrid PZT/FBG system has its own limitations. Because electrical cables are still required for the excitation of the PZT transducers, this hybrid system does not take full advantage of the optical fibers used for the FBG sensors.

The objective of this study is to develop a fully integrated measurement system that uses a single laser source and optical fibers for transmitting power and data necessary for PZT- and FBG-based guided wave generation and sensing. First, a tunable laser is used as a single laser source, and the laser beam of this laser is divided into two beams by using an optical coupler. Then, one laser beam is modulated, amplified and converted to an electric signal to actuate the PZT transducer. The other laser beam is used with the FBG sensor for measuring high-speed strain changes induced by guided waves. The feasibility of the proposed hybrid system is experimentally tested on a thin aluminum plate and on a carbon steel cylinder. There can be dual-line or single-line approach according to the number of optical fibers for connecting the PZT transducer node and the FBG
sensor node. Since the single-line scheme is more attractive for single transmission in SHM of real field structures, this study also investigated the feasibility of the single-line scheme. The uniqueness of these systems lie in the use of optical fibers for power and data transmission needed for guided wave excitation and sensing to overcome the aforementioned issue with conventional electrical cables.
CHAPTER 2
WORKING PRINCIPLES

2.1 Basic schemes

Figure 1 shows the overall schematics of the proposed system. First, a tunable laser is used as a common power source for both guided wave generation and sensing. As for guided wave generation, a desired reference signal is created by an arbitrary waveform generator (AWG), and the laser beams is modulated accordingly using an optical modulator. Then, a fiber amplifier increases the power level of the modulated laser beam before it is transmitted through a long
range optical fiber. When the laser beam is delivered to the PZT transducer node, a photodiode within the PZT node converts the laser beam into an electrical signal and a transformer increases the voltage level of the electrical signal. Finally, a PZT transducer is excited and guided waves are generated in a structure. A similar laser based system is developed for wireless PZT excitation by Park et al. (2009).

As for guided wave sensing, the laser beam passes through an optical circulator that links the optical fibers that are connected to the optical coupler, FBG sensor, and photodiode. The incident laser beam through the optical circulator is reflected from the FBG sensor at a specific wavelength, and circulated back to the photodiode. Then, the photodiode converts the reflected laser to an electrical signal. Finally, the intensity change of the reflected laser beam at the specified wavelength is related to the dynamic strain induced by propagating guided waves.

There can be a dual-line scheme and a single-line scheme in the proposed system with respect to the number of the optical fiber for guided wave generation and sensing. Figure 2 (a) shows the conventional hybrid system. An electrical cable is used in the wave generation part, which is known to be vulnerable to EMI and power/data attenuation. Figure 2 (b) shows the dual-line scheme which uses the two optical fibers for both guided wave generation and sensing. The tunable laser beam is divided into two beams, and the one is modulated and amplified for guided wave generation while the other is directed to the FBG sensor node. Figure 2 (c) shows the single-line scheme which enables guided wave generation and
sensing by using the modulated tunable laser beam through the single optical fiber. This paper contains the experimental validations on the dual-line scheme and preliminary study on the future development of single-line scheme for SHM of large and long-ranged field structures.

Figure 2. Comparison of the three different schemes of the guided wave generation and sensing system
Chapter 2 Working principles

2.2 Guided wave generation using a PZT transducer

The first step in guided wave generation is the creation of a desired input waveform by using the AWG. As shown in Equation 1, a seven-peak tone-burst signal, which is a cosine function modulated with a Hanning window, is used for the guided wave generation. Throughout this paper, the signal generated by the AWG is referred to as the “reference signal”; further, the term “input signal” refers to the electrical signal measured right before being applied to the PZT for the guided wave excitation.

\[
y(t) = \exp \left[ -\frac{1}{2} \left( \frac{2\pi ft}{7} \right)^2 \right] \cos(2\pi ft),
\]

where \( f \) is the driving frequency.

The reference signal is sent to the optical modulator, which modulates the power intensity of the tunable laser in accordance with the reference signal. The principle of the optical modulator is based on electro-optic effects (Wilson et al. 1998). As the electric field produced by the reference signal is applied across an optical medium, the polarizability and the refractive index of the medium vary, resulting in a change in the light intensity.

Figure 3 shows the intrinsic transfer function of the optical modulator. It illustrates the relationship between the reference signal and the light intensity of the laser beam transmitted through the optical modulator. \( V_x \) denotes the voltage where the transmitted light intensity is maximized. Because of the nonlinear character of the intrinsic transfer function, it is necessary to find a region of the
transfer function where the light intensity varies linearly with the applied voltage. The maximum linearity can be achieved near the 50% transmission point since the slope of the transfer function is close to linear. For this reason, a DC bias is added to shift the zero level of the original reference signal to the 50% transmission point ($\pi/2$). Because the laser is attenuated during the modulation process, the laser power is amplified using an erbium-doped fiber amplifier before transmitting the beam for PZT excitation. When the modulated laser beam passes through the erbium-doped fiber amplifier, the energy of the pumping photon in the fiber excites Er3+ ions, and the stimulated emission of Er3+ ions amplifies the laser power (Wilson et al. 1998).

Figure 3. Intrinsic transfer function of the optical modulator, which modulates the light intensity on the basis of the reference signal.
In order to generate guided waves by using the PZT transducer, the photodiode converts optical power to electrical power. Among the various types of photodiodes, \( pn \)-junction-type devices are widely used because of their small size, high-speed conversion, and good sensitivity (Kasap et al. 2001). Figure 4 shows the structure of a \( pn \)-junction photodiode (Khare et al. 2004). \( E_C \), \( E_F \), and \( E_V \) are the energy levels of the conduction band, Fermi band, and valence band, respectively. When a photon strikes the depletion region, its energy is absorbed by an electron. When the energy acquired by the electron is greater than that of the band gap (\( E \geq E_B \)), the electron gets detached from its hole and moves from the valence band into the conduction band. The separated electrons and holes experience a strong electric field and drift towards the n and p sides, respectively. The electric current that results from the drifting of the holes and the electrons is proportional to the number of incident photons.

![Figure 4. Structure of a pn junction](image_url)
In order to excite a typical PZT transducer used for the guided wave generation, a voltage level of at least 1-2 V is required (Greve et al. 2007). However, the photodiode used in this study does not produce a voltage level sufficient to excite the PZT transducer. For instance, Figure 5 shows that, even with a rapid increase in $I_{ph}$ up to 200 mA, $V_p$ remains under 0.35V (Park et al. 2009 and Wilson et al. 1998). In the figure, $I_0$ is the reverse saturation current (40 μA), $e$ is the electron charge ($1.6 \times 10^{-19}$ C), $k_B$ is the Boltzmann constant (86.1 μeV/K), $T$ is the absolute temperature of the photodiode (300 K), and $n$ is the ideality factor that depends on the semiconductor material (1.48).

\[
V_p = \frac{n k_B T}{e} \ln \left( \frac{I_{ph}}{I_0} + 1 \right)
\]

Figure 5. Relationship between the photocurrent ($I_{ph}$) and the output voltage ($V_p$) for a typical $pn$-junction-type photodiode. It shows that the output voltage is limited despite the considerable increase in the photocurrent from 0 mA to 200 mA. $I_0$, $e$, $k_B$, $T$ and $n$ are the reverse saturation current, quantity electron charge, Boltzmann constant, absolute temperature, and ideality factor, respectively.
2.3 Signal distortion in guided wave generation

Here, an electrical circuit analysis was performed to estimate the effect of the PZT transducer node on the input signal distortion. A commercial circuit analysis software program PSPICE was used for the circuit analysis (http://www.cadence.com). Figure 6 shows the equivalent circuit model of the PZT transducer node. The PZT transducer is modeled as an RC circuit with $C_{PZT}$ of 2.3 nF and $R_{PZT}$ of 25 $\Omega$. Other parameters in the equivalent circuit are $L_1$ of 0.075 mH and $L_2$ of 1.07 mH, $R_p$ of 1$\text{M}\Omega$ and $R_S$ of 1 $\Omega$, respectively. The photocurrent ($I_{ph}$) has a tone-burst waveform with a frequency of 150 kHz and arbitrary amplitude.

![Equivalent circuit model of the PZT transducer node for guided wave generation](image)

Figure 6. Equivalent circuit of the PZT transducer node for guided wave generation
Chapter 2 Working principles

Figure 7. Effect of the photodiode and transformer on phase distortion and time delay of the input signal

Through the circuit analysis, time delay and the phase distortion of the input signal with respect to the reference signal are observed as shown in Figure 7. The input signal is delayed by 0.67 \( \mu \text{sec} \) with respect to the reference signal during the conversion to electric signals at the photodiode, and by 0.74 \( \mu \text{sec} \) during the voltage amplification at the transformer. Each signal is normalized with respect to its peak-to-peak value for a better comparison of the waveforms. This circuit analysis shows that the characteristics of the photodiode and the transformer can attribute to the distortion and the time delay of the input signal. The photodiode requires time to activate the electrons in the \( pn \) junction, and this
produces a slight time delay and phase distortion in the input signal. This time delay effect becomes even more eminent when the light intensity changes faster at a higher driving frequency as in this study. The transformer can also contribute to the distortion of the input signal, since the flux change of the magnetic field of the transform is complex and introduces time delay.

Another source of signal distortion is the optical modulator. As previously mentioned in Figure 3, the linear relationship between the reference signal and the modulated light intensity can be maximized by biasing the voltage level of the reference signal near the 50% transmission point. However, there still exists a certain level of nonlinearity between the reference signal and the modulated light intensity, and this nonlinear effect becomes more prominent if the voltage range of the reference signal extends beyond the acceptable linear range. Because of the various sources of signal delay and distortion, the discrepancy between the reference and the input signals is inevitable in practice. A scheme to minimize such a discrepancy will be presented in the following sections.
2.4 Guided wave sensing using a FBG sensor

An FBG is a periodic and permanent variation in the refractive index of a fiber core. It acts as an optical filter for the light travelling along an optical fiber. It reflects light only in a certain narrow bandwidth that is centered around the Bragg wavelength $\lambda_B$. $\lambda_B$ is defined as follows:

$$\lambda_B = 2N_{\text{eff}}A,$$

(3)

where $A$ is the grating period and $N_{\text{eff}}$ is the mean refractive index of the FBG.

Equation 3 shows that a change in either $N_{\text{eff}}$ or $A$ causes a shift of $\lambda_B$. $N_{\text{eff}}$ and $A$ are dependent on temperature and external strain. The first-order approximation of the fractional change in the Bragg wavelength $\frac{\Delta \lambda_B}{\lambda_B}$ is given as follows:

$$\frac{\Delta \lambda_B}{\lambda_B} = C_\varepsilon \varepsilon_z,$$

(4)

where $\varepsilon_z$ is the applied strain, and $C_\varepsilon$ is a constant that depends on material properties (Bass et al. 2002). Therefore, the strain induced by guided waves in the structure can be related to a shift in $\lambda_B$.

Conventional FBG interrogators such as an optical spectrum analyzer, Fabry–Perot filter, and Mach–Zehnder interferometer have been widely used for low-frequency dynamic strain measurement. However, these conventional interrogators are not suitable for guided wave sensing because of their low sampling rates. Normally, conventional interrogators have a sampling rate of less
than 1 kHz, while the frequency range of interest for the guided wave measurement is more than 100 kHz. Therefore, a new method for a guided wave measurement with a tunable laser and FBG sensors is adopted in this study to measure high-speed strain changes (Betz et al. 2003).

Figure 8. Spectra of the FBG and the tunable laser. The strain induced by the guided waves causes variations in $\lambda_B$; the corresponding FBG spectrum is shifted horizontally. Then, the intensity of the laser reflected from the FBG varies with respect to the change in the FBG spectrum. Therefore, it is possible to measure guided waves by simply detecting the change in the reflected laser intensity at the FBG.

Figure 8 shows the spectrum curves of the FBG sensor (dashed line) and the tunable laser (solid line). The spectrum of the FBG sensor has a broad bell-
shaped distribution centered around $\lambda_B$, and the entire spectrum shifts horizontally as the FBG sensor experiences strain. On the other hand, the spectrum of the tunable laser is considerably narrower than that of the FBG sensor, and the central wavelength of the spectrum is fixed at a certain value throughout the measurement process. When the tunable laser sends light to the FBG sensor, some of the incident light is reflected. The optical intensity of the reflected light, the grating’s reflectivity, is proportional to the overlapped area between the FBG and the tunable laser spectra. Therefore, the strain that the FBG sensor experiences causes the horizontal shift of the FBG spectrum and subsequently the variation in the FBG reflectivity. This change in the reflective light intensity is measured by the data acquisition component composed of a photodetector and an oscilloscope. The linear relationship between the strain and the FBG reflectivity is guaranteed by ensuring that the central wavelength of the tunable laser falls within the linear range of the FBG spectrum corresponding to 40–80% of the maximum reflectivity of the grating, as shown in Figure 8 (Betz et al. 2003, Tsuda et al. 2004).
Chapter 2 Working principles

2.5 Signal distortion in FBG sensing

Guided wave sensing by using the FBG sensor generally guarantee reasonable performances in the dual-line scheme. However, there can be signal distortion problems in the single-line scheme. Figure 9 shows the distorted response signal from the FBG sensor in the single-line scheme. In this case, the tunable laser is modulated and then directed to the FBG sensor node. Thus, the modulated input signal component is also contained in the FBG response signal. Since the signal level of the input signal is very high compared with that of the response signal, there is a long decaying tail of the large input signal. Therefore, low-level response signals can be severely distorted by the decaying tail. To address this problem, special kinds of filtering methods can be considered. Or, this problem can be avoided by simply increasing the distance between the two points of wave generation and sensing.

Figure 9. Distorted response signal in the single-line scheme
CHAPTER 3
EXPERIMENTAL SETUP

3.1 Device configuration

Figure 10. Overall configuration of the experimental setup

In order to validate the feasibility of the proposed guided wave generation and sensing system, several experimental tests were performed. Figure 10 shows the overview of the experimental setup corresponding to the conceptual schematics of Figure 2. The proposed system consists of five subcomponents: a common laser source, a wave generation component, a PZT excitation node, an FBG sensor node, an optical coupler, and a tunable laser.
Chapter 3 Experimental setup

As the common laser source, the tunable laser source (AQ4321A, ANDO) provides the light necessary for guided wave generation and sensing to both the PZT and the FBG. For power/data transmission, single-mode optical fibers (SMF-28) are used. The power level of the tunable laser is set to 1.58 mW and divided into two branches at the optical coupler (Smart Light Technology). The wave generation component is composed of the AWG, optical modulator, and optical amplifier. Using the AWG (33220A, Agilent), a reference signal with a peak-to-peak voltage of 1.85 V and a driving frequency of 150 kHz was generated. Then, the modulator and the amplifier modulate and amplify the light intensity in accordance with the reference signal and deliver light to the PZT node via an optical cable.

The PZT transducer node consists of the photodiode, transformer and PZT transducer. The InGaAs-type photodiode (FGA04, Thorlabs) converts the optical power into electrical power. It has a response range of 800 nm to 1800 nm and a rising time of 100 psec. The transformer with a coil turn ratio of 20 is used for increasing the voltage level of the converted electrical power in order to excite PZT A in shown Figure 10. The guided waves generated by PZT A propagate through the specimen, and the waves are measured by the FBG sensor 213 mm that is placed at a distance of from PZT A. For the guided wave measurement, the other tunable laser beam divided by the optical coupler is delivered to the FBG. The laser beam reflected from the FBG sensor is redirected to the data acquisition
component by using the optical circulator (Agiltron).

The data acquisition component is composed of the photodetector, optical circulator, and oscilloscope. The photodetector (PDA 10CS-EC, Thorlabs) is an amplifiable-type one that can detect light with a wavelength range of 150-4800 nm. Finally, the oscilloscope (TDS 30254B, Tektronix) measures the electrical signal with a sampling rate of up to 25 MHz.
3.2 Target specimens

(a) Plate specimen used in the dual-line scheme

(b) Plate specimen used in the single-line scheme

(c) Cylinder specimen

Figure 11. Test specimens used in this experiment
Figure 11 (a) shows the test specimens used in this experiment for the dual-line scheme. The aluminum plate specimen has the dimensions of 453 mm X 197 mm X 6 mm. Two PZT transducers and a FBG sensor are attached on the specimen. The PZT transducers are PSI-5AE type and their dimensions are 10 mm X 10 mm X 0.508 mm. The FBG sensor has the Bragg wavelength of 1548.3 nm and the grating length of 10 mm and use a single mode optical fiber. Both PZT B and the FBG sensor are 213 mm away from PZT A horizontally, and they are vertically apart about mm.

Figure 11 (b) shows the test specimen for the single-line scheme. The aluminum plate specimen has the dimensions of 600 mm X 400 mm X 6 mm. A larger specimen was used to avoid signal distortion in the single-line scheme that is discussed in the previous section. The distance between the PZT A and the FBG sensor has been increased from 213mm to 550mm. The same type of FBG sensor is used only with different Bragg wavelength of 1550.0 nm.

Figure 11 (c) shows the cylinder specimen to validate the double-line scheme for field applications. Since many field structures have cylindrical shapes, this study tried to increase the availability for real SHM cases. The carbon steel cylinder specimen has the outer diameter of 114.3 mm and the thickness of 6 mm. A macro carbon composite (MFC) transducer was attached due to the curved shape of the cylinder. The distance between the MFC and the FBG sensor was 400 mm. The same type of FBG sensor is used only with different Bragg wavelength of 1550.0 nm.
CHAPTER 4
EXPERIMENTAL RESULTS

4.1 Introduction

In order to validate the feasibility and the effectiveness of the proposed integrated system, several experiments were performed. First, the reference signal generated by the AWG and the input signal applied to PZT A were compared, and a scheme to minimize the discrepancy between the two signals was introduced. Next, the power transmission efficiency for the guided wave excitation component was quantitatively investigated. Then, comparisons between the excitation using the tunable laser and the AWG, and the sensing using the PZT transducer and the FBG sensor were conducted. Detailed experimental results will be discussed in the following subsections.
4.2 Generation of the input signal

Figure 12. Distortion of the input signal with respect to the reference signal. Both shape change and time delays of the input signal are observed.

Figure 12 shows the reference (dotted line) and the input (solid line) signals. Each signal is normalized by its peak-to-peak value for a better comparison. As described in Equation 1, a seven-peak toneburst signal with a central frequency of 150 kHz and a peak-to-peak voltage of 1.85 V is used as the reference signal. The input signal, which is the actual signal applied to the PZT, has a peak-to-peak voltage of 10.8 V and a central frequency of 145 kHz. The comparison of these two signals reveals that the input signal is delayed by approximately 1.3 μsec with
respect to the reference signal and its shape is altered. The time delay and the
waveform distortion are mainly attributed to the modulator, photodiode, and
transformer as previously mentioned.

In order to minimize the difference between the reference and the input
signals, a transfer function between the two signals was experimentally identified
and a revised reference signal, which could bring the input signal closer to the
ideal reference signal, was computed. The empirical transfer function, $H(\omega)$, was
identified from the measured reference and input signals as follows (Maia et al.
1997):

$$H(\omega) = \frac{S_{XY}(\omega)}{S_{XX}(\omega)} = \frac{\sum X(\omega)Y^*(\omega)}{\sum X(\omega)X^*(\omega)}, \quad (5)$$

where $X(\omega)$ and $Y(\omega)$ are the Fourier transforms of the reference and input
signals, respectively. $S_{XY}$ is the correlation between $X$ and $Y$, and $*$ is a complex
conjugate operator. $S_{XX}$ is defined similarly. For the estimation of the empirical
transfer function, the values of both the reference and the input signals were
measured 20 times and averaged in the frequency domain. From the empirical
transfer function, a revised reference signal, which brought the updated input
signal closer to the ideal reference signal, was derived, as shown in Figure 13.
Figure 13. Revised reference signal used for generating the desired input signal

Figure 14. Compensation of the input signal distortion by using the empirical transfer function

Figure 14 shows that the discrepancy between the ideal reference and the improved input signals can be minimized using the compensation scheme. The
improvement in the input signal was quantitatively computed by using the following equation:

\[ \rho_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y}, \]  

(6)

where \( X(t) \) and \( Y(t) \) are the normalized versions of the original reference and input signals, respectively. \( \mu_X \) and \( \mu_Y \) are the mean values of \( X \) and \( Y \), and \( \sigma_X \) and \( \sigma_Y \) are the standard deviations of \( X \) and \( Y \). The cross-correlation coefficient between the two signals improved from 0.7983 to 0.9651.
4.3 Power levels in laser transmission process

Figure 15. Power levels at various stages of the guided wave generation process

Figure 15 shows the power levels at the various stages of the guided wave generation process. First, the power level of the tunable laser was set to 1.58 mW. The power level was decreased to half, 0.782 mW, when the tunable laser beam was divided into two. After the modulation of the laser beam, the power level was reduced to 0.181 mW. Then, the fiber amplifier increased the power level to 124 mW to achieve a sufficient power level for the guided wave generation. Finally, the photodiode changed the laser beam into electrical power, and the power level at the PZT transducer node was 47.8 mW. The overall power efficiency of the guided wave generation process was 38.6%.
4.4 Experimental validation for the dual-line scheme

Figure 16. Comparison of FBG response signals corresponding to the AWG excitation (Reference signal: dotted line) and the tunable laser (TL) excitation (Input signal: solid line).

Figure 16 shows the response signals excited by either the AWG or the tunable laser and measured by the FBG sensor. The excitation voltages of the AWG and the tunable laser were 10.0 V and 10.8 V, and their corresponding peak-to-peak responses were 9.26 mV and 9.42 mV, respectively. Here, each response signal was normalized with respect to its peak-to-peak value. The cross-correlation coefficient between the two response signals was 0.986. This result shows that the tunable laser can guarantee a reasonable performance for the guided wave generation.
Figure 17 shows the response signals generated by the AWG and measured by PZT B and the FBG sensor. Here, each response signal was also normalized with respect to its peak-to-peak value. The peak-to-peak values of the response signals measured by PZT B and the FBG sensor were 11.1 mV and 15.2 mV, respectively. The cross-correlation coefficient of the two response signals was 0.374, which implied the quantitative difference between the two signals. The discrepancy between the two signals was responsible for the different characteristics between the FBG sensor and the PZT transducer: The PZT transducer measured waves coming from all directions while the unidirectional FBG sensor measured the responses only along the wave-propagation direction.
The signal-to-noise ratio (SNR) of each response signal was computed as follows:

$$\text{SNR} = \frac{\text{RMS}(y_1 - \bar{y})}{\text{RMS}(e_1 - \bar{e})} = \frac{\sqrt{\frac{\sum (y_1 - \bar{y})^2}{N}}}{\sqrt{\frac{\sum (e_1 - \bar{e})^2}{M}}}$$

(7)

where $y_1$ is the voltage level of the response signal and $e_1$ is the noise level of the response signal without the input signal. Further, $\bar{y}$ and $\bar{e}$ are the mean values of $y_1$ and $e_1$, and $N$ and $M$ are the corresponding number of data points in the time domain. The SNR of the PZT response was 327, while that of the FBG sensor was 94. Although the SNR of the FBG sensing was lower than that of the PZT sensing, the effect of noise was negligible in both the sensing cases. Similar comparisons between PZT and FBG sensing have been performed by other researchers (Betz et al. 2003, Yuan et al. 2004, Tsuda et al. 2006).

Figure 18. Theoretical dispersion curves of the S0 and A0 modes. The group velocities of the S0 and A0 modes were estimated from the dispersion curves in order to calculate the arrival times of the wave components.
In order to further analyze the response signal measured by the FBG sensor, the arrival times of each mode in the measured response signal were estimated from the theoretical dispersion curves shown in Figure 18. The group velocities of the S0 and A0 modes were estimated to be 5.088 m/ms and 3.055 m/ms, respectively.

(a) Wave propagation along the direct path (213 mm)

(b) Reflections from the side boundaries (290 mm)
Figure 19. Multiple wave propagation paths are examined in order to identify the wave components (waves along the direct path, and reflections from the side and end boundaries) in the response signal.

Figure 19 shows the wave paths in the test specimen. Figure 19 (a), (b), and (c) represent the direct path (213 mm), side reflection path (290 mm), and end reflection path (453 mm), respectively. The arrival times of the S0 and A0 modes corresponding to each wave path are given in Table 1.

<table>
<thead>
<tr>
<th>Wave mode</th>
<th>Wave path</th>
<th>Arrival time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>Direct</td>
<td>0.04186</td>
</tr>
<tr>
<td>S0</td>
<td>Side reflection</td>
<td>0.05702</td>
</tr>
<tr>
<td>A0</td>
<td>Direct</td>
<td>0.06972</td>
</tr>
<tr>
<td>S0</td>
<td>End reflection</td>
<td>0.08903</td>
</tr>
<tr>
<td>A0</td>
<td>Side reflection</td>
<td>0.09497</td>
</tr>
<tr>
<td>A0</td>
<td>End reflection</td>
<td>0.14828</td>
</tr>
</tbody>
</table>
Chapter 4 Experimental results

Figure 20. Comparison of wave components measured by PZT B and the FBG sensor. The AWG is the common excitation source, and each wave component is identified by its estimated arrival time.

On the basis of the arrival times of each mode listed in Table 1, wave modes in the response signals were identified as shown in Figure 20. Near the arrival times of the S0 and A0 modes along the direct wave propagation path and the reflections from the end boundaries, the two response signals measured by the PZT and the FBG were similar. These experimental results confirm that the FBG sensor can effectively detect guided waves in the test structure. However, at the other time points, these two signals were significantly different from each other. These differences were mainly due to the different characteristics of the PZT and the FBG sensors.
Figure 21. Comparison of the response signals from the FBG sensors in different schemes

In this section, a study for utilization of single line scheme is discussed. Figure 21 shows the response signal from the FBG sensor in the single-line scheme as well as the response signals in the conventional and dual-line scheme. The specimen used in this experiment is shown in Figure 11 (b), and it is larger than that of dual-line scheme to avoid the aforementioned signal distortion and loss of first arrival wave components. The excitation voltage is 19.0 V and the voltage level of the
response signal from the FBG sensor is 4.5 mV in the single-line scheme. For comparison with other guided wave generation and sensing schemes, additional experiments were performed on the same specimen by using the conventional hybrid scheme and the dual-line scheme. The excitation voltages in the comparison schemes are 9.5 V and 18.0 V, respectively. The voltage levels of the response signals in the two comparison schemes are 4.12 mV, 3.97 mV respectively. By calculating theoretical group velocity, the first arrival component of S0 mode is successfully detected as in other schemes. The signal-to-noise ratio (SNR) level of the response signal in the single-line scheme is 10.8 dB, while SNR levels of conventional and double-line scheme are 20.2 dB and 36.1 dB, respectively. Although SNR levels vary according to the bonding condition and external vibration, they are relatively reasonable for applications to damage detection techniques. Therefore, it is concluded that the single-line scheme has potential to further application to SHM of large and long-ranged field structures.
4.6 Applications for a cylindrical structure

In this section, the proposed technique with the dual-line was applied to a cylinder specimen. The specimen used in this experiment is shown in Figure 11 (b) and described in section 3.2. The excitation voltage is 5.0 V and the voltage level of the response signal from the FBG sensor is 0.1 mV in the single-line scheme. The signal-to-noise ratio (SNR) level of the response signal in the single-line scheme is 7.1 dB. SNR level can be increased with the high level of excitation laser input power.

![Dispersion Curve (Group Speed)](image)

At the driving frequency of 150 kHz, Wave velocity = 3100 m/s

Figure 22. Dispersion curve of the carbon steel cylinder specimen

To identify the wave components, finite element analysis was performed and compared with the experimental results. Figure 22 shows the dispersion curve
of the target cylinder specimen. Since this study excited only one MFC transducer, the non-axi-symmetric excitation mostly excited several specific flexural modes. At the driving frequency of 150 kHz, several flexural modes (mainly F(1,1) and F(1,2)) form a wave group with almost same group velocities. The velocity of the wave group is almost equal to 3100 m/s.

Figure 23 shows the configuration of the target cylinder specimen. To identify the initial arrival wave packets, this study considered four wave paths considering a) direct path from the MFC sensor to FBG sensor (M-F) to F; b) reflection from the left end (M-L-M-F); c) reflection from the right end (M-F-R-F); d) reflections from the left and right ends (M-L-M-F-R-F). Table 2 shows the theoretical arrival times of the four initial wave packets from the derived group velocity and the four possible wave paths.
Chapter 4 Experimental results

Table 2. Theoretical arrival times of the four initial arrival wave packets

<table>
<thead>
<tr>
<th>Wave path</th>
<th>Wave path</th>
<th>Arrival time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-F</td>
<td>Direct</td>
<td>1.290</td>
</tr>
<tr>
<td>M-L-M-F</td>
<td>Reflected once at the left end</td>
<td>1.153</td>
</tr>
<tr>
<td>M-F-R-F</td>
<td>Reflected once at the right end</td>
<td>1.936</td>
</tr>
<tr>
<td>M-L-M-F-R-F</td>
<td>Reflected once at both ends</td>
<td>2.116</td>
</tr>
</tbody>
</table>

Figure 24. Response signals from the FEM analysis
On the basis of the theoretical arrival times of four initial wave packets listed in Table 2, the four initial wave packets from the FEM analysis and experiments were identified as shown in Figure 24 and Figure 25, respectively. FEM analysis was performed using PZFlex. Even though the entire waveforms showed some degree of discrepancy, the two response signals in the initial stage show good similarity. From the comparison with the responses from the experiment and FEM analysis, and from the wave packet identification, it is concluded that the proposed hybrid scheme has potential to further application to SHM of cylindrical and pipeline structures.
CHAPTER 5
CONCLUSION

This paper proposes a new guided wave generation and sensing system that uses a single tunable laser source and optical fibers. The proposed system combines PZT-based actuation and FBG-based sensing. First, the single tunable laser source is used as the common power source, and the laser beam is divided into two beams. One laser beam is used for the guided wave generation. This beam is modulated with the optical modulator and AWG in order to generate an arbitrary waveform. This modulated laser is amplified by the fiber amplifier and converted into an electrical signal by the photodiode. The converted electrical signal then excites the PZT transducer and generates guided waves in the test structure. On the other hand, the other laser beam is incident on the FBG sensor. The light intensity of the laser reflected from the FBG changes in proportion to the strain variation induced by the guided waves in the specimen. This reflected laser beam is transmitted to the photodiode and is converted into an electrical response signal.

The feasibility of power/data transmission in the proposed system is demonstrated by several experiments. Through comparison of the response signals from the conventional and the proposed schemes, the results confirm that the tunable laser can exhibit reasonable performance in guided wave generation. Also in case of dual-line scheme, the results guarantee feasibility of guided wave sensing using the FBG sensor. To check the feasibility of FBG sensing, the arrival
time of each wave mode in each wave path was calculated. Then, the wave modes in the response signals were identified considering directionality of the PZT transducer and the FBG sensor. This study also confirms the feasibility of single-line scheme for future application to SHM through preliminary experimental studies. Finally, this study applied the proposed technique to a cylinder specimen to check the feasibility for the applications to the pipeline structures.

Since only optical cables are used for guided wave generation and sensing, the proposed system has several advantages over the conventional hybrid system: It can eliminate EMI, transmit data and power over a long distance without considerable attenuation and noise contamination, simplify the measurement system, and make the cable installation easier. Further improvement is underway so that the system uses only a single optical cable for multipoint guided wave excitation and sensing.
요 약 문

단일 레이저 광원과 광섬유를 활용한 유도파 생성 및 계측 시스템

유도파를 이용한 사회기반시설물의 구조물건진단모니터링이나 손상감지에는 지급까지 활발하게 이루어지고 있다. 압전센서와 FBG센서는 무게와 부피가 작아 구조물에 쉽게 일체화될 수 있다는 장점 때문에, 유도파를 생성하고 계측하는 데 많이 쓰여왔다. 능동센서가 가능한 압전센서와 전자기감섭현상에 무관한 FBG센서의 장점을 모두 살리기 위하여, 두 센서를 모두 활용한 복합형 센sing기법이 최근 연구되어 오고 있다. 그러나 기존의 복합형센서기법은 유도파를 생성하기 위하여 기존의 전력케이블을 사용하기 때문에, 유도파의 생성 과정에서 전자기적간섭으로 인한 신호왜곡에 취약하고, 원거리 전력/신호 송신의 경우 출력이 감소되어 효율이 떨어지는 문제점이 있다. 따라서 본 연구에서는 단일한 레이저 광원과 광섬유로 기존의 전력케이블을 대체하고자 하였다. 이를 통하여 기존의 전력케이블이 조례할 수 있는 전자기적간섭에 의한 신호왜곡과 원거리 신호전송에 의한 출력감소, 노이즈에 취약한 문제 등을 해결할 수 있다. 파장변조레이저를 단일광원으로 하여, 일부 광선은 변조과정을 거쳐 유도파신호를 압전센서로 생성하고, 나머지 광선은 FBG센서로 입력하여 유도파로 인한 구조물 변위의 변화를 고속으로 감지한다. 본 기법의 유용성은 몇 가지 실내실험을 통하여 실험적으로 증명하였다.
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