Baseline-free pipeline monitoring using optical fiber-guided laser ultrasonics
Hyeonseok Lee, Jinyeol Yang and Hoon Sohn

Structural Health Monitoring 2012 11: 684 originally published online 15 August 2012
DOI: 10.1177/1475921712455682

The online version of this article can be found at:
http://shm.sagepub.com/content/11/6/684
Baseline-free pipeline monitoring using optical fiber–guided laser ultrasonics

Hyeonseok Lee, Jinyeol Yang and Hoon Sohn

Abstract
This study develops an optical fiber–guided laser ultrasonic system and baseline-free damage detection method that enables structural health monitoring of pipelines employed under a high-temperature environment of nuclear power plants. First, this study designs embeddable optical fibers and fixing devices, so that the laser beams used for ultrasonic excitation and sensing could be transmitted between laser sources and target pipe surfaces through the optical fibers. All devices are specially designed for a high-temperature environment up to 300°C. Then, a damage detection method is developed to identify typical pipe defects without any previous baseline data. This technique is based on the premise that multiple identical wave paths exist in an intact axisymmetric pipe, but the similarity among the ultrasonic signals obtained from these identical wave paths breaks down when there is a nonaxisymmetric defect. The feasibility of the proposed technique has been experimentally verified using a stainless steel pipe specimen under a high-temperature environment.

Keywords
Pipeline, structural health monitoring, nuclear power plants, laser ultrasonics, optical fiber, high temperature, baseline-free damage detection, outlier analysis

Introduction

It has been reported that structural integrity of nuclear power plants (NPPs) continues to deteriorate. About 78% of all NPPs worldwide have been in operation over 20 years and 30% over 30 years.1 Furthermore, many countries are facing growing public opposition to the construction of new NPPs and under pressure to shut down existing NPP facilities. Therefore, nuclear regulatory authorities in many countries have recently tightened their safety measures and implemented strict inspection criteria for operational NPPs.

Conventional NPP pipeline inspections have been based on periodic nondestructive testing (NDT).2,3 Despite many merits of NDT techniques, they have their own limitations. First, NDT normally requires a periodic overhaul of the NPP facilities, reducing its power production efficiency and causing the secondary damage. Also, NDT inspections of NPPs can be performed only by certified personnel, so the inspection process inevitably becomes labor-intensive and expensive. More importantly, there are several critical points, which cannot be easily accessed by conventional NDT techniques.4

In order to complement existing NDT techniques, the industry is developing structural health monitoring (SHM) systems for NPP management. Compared to NDT, SHM techniques can provide the following potential benefits: (a) automated and continuous monitoring of NPP facilities, (b) reduction in overhaul frequency, cost, and labor necessary for NPP inspections, and (c) monitoring of hidden critical spots, which have been difficult to inspect using conventional NDT techniques.5,6

Current monitoring efforts for pipe structures can be categorized into two: global and local monitoring techniques. Global monitoring techniques identify structural damage by measuring dynamic characteristics of a structural system such as accelerations7–9 and strain/stress.10–12 Global monitoring is performed based on the premise that if a structural defect, such as wall thinning or cracking, were large enough to affect the dynamic characteristics of the structure, these would be
reflected on the measurements. On the other hand, local monitoring aims to identify, localize, and quantify structural defects in an earlier stage than global techniques. For example, ultrasonic waves generated and measured by magnetostrictive sensors (MSSs)\textsuperscript{13-15} or electromagnetic acoustic transducers (EMATs)\textsuperscript{16-18} are used to detect even a small defect based on the interact of the ultrasonic waves with the defect.

However, several challenges have hampered the application of SHM to pipe structure used in NPPs. First, it requires permanent installation of distributed sensors that can survive harsh operational conditions of NPPs such as temperature and radiation.\textsuperscript{19} Second, SHM techniques are normally less accurate than NDT techniques in quantifying the damage location and level, and they are vulnerable to false alarms induced by the operational variations.

This study develops an optical fiber–guided laser ultrasonic system and a damage detection method specifically designed for NPP pipeline structures. Ultrasonic waves are generated using a Nd:YAG laser and sensed by another laser interferometer. The laser beams from the laser sources to the target pipe surfaces are guided and transmitted using embeddable optical fibers. Then, an autonomous damage detection method tailored to the laser ultrasonic system is developed based on the axisymmetric nature of pipe structures. The proposed techniques have the following advantages over the existing techniques: (a) the proposed optical fiber–guided laser ultrasonic system can be applied to NPP pipe network operating under high-temperature environment up to 300°C; (b) the fiber-guided system can be readily embedded to monitor pipelines covered with insulators; and (c) because the proposed damage detection algorithm does not require any previous baseline data, environmental and operational variations such as temperature change and vibration due to water flow inside pipes barely affect the damage detection performance.

**Optical fiber–guided laser ultrasonic system**

Figure 1 shows a schematic diagram of the optical fiber–guided laser ultrasonic system. A pulse laser is transmitted through an optical fiber to generate ultrasonic waves on a pipe surface, and an interferometer connected to a separate optical fiber is used to measure the corresponding response at another point on the pipe surface. Then, there are additional components such as focusing modules for laser beam focusing and stainless steel strips used for fixing the focusing modules to the pipe surface. More details of the measurement system and its components are described below.

**Optical fiber–guided laser ultrasonic generation**

Figure 2 shows the detailed configuration of the optical fiber, the laser source, and the connecting components required for optical fiber–guided laser ultrasonic generation. When a solid surface is illuminated by a high-power pulse laser, a localized heating and the corresponding elastic expansion is produced at an infinitesimal area of the surface, acting as an ultrasonic wave source.\textsuperscript{20} Here, the laser duration, power level, and beam size need to be carefully tuned and maintained to generate elastic waves without ablating the surface. Ablation typically occurs for metals with a power density above $10^7$ W/cm\textsuperscript{2},\textsuperscript{21} but this value varies depending on their material properties as well as surface conditions. In this study, a 1064-nm Nd:YAG pulse laser (Brilliant Ultra; Quantel) is used. The excitation energy per unit pulse, the pulse duration, and the repetition rate of the laser beam are set to 10 mJ, 8 ns, and 20 Hz, respectively, to avoid ablation.

A metal-coated multimode fiber with 1000 μm core diameter (HPSUV 1000CB; Oxford Electronics) is used to carry the laser beam from the laser source to the target point on the structure. Here, a multimode fiber is used for high-power laser transmission. This multimode fiber is made of step-index silica where the core and the cladding are made of pure silica and doped silica, respectively. According to the manufacturer specification, the fiber is also radiation resistant, and the CuBall metal coating allows the operation of the optical fiber up to 500°C.

The high-power laser beam needs to be properly focused to the target surface using focusing lenses for an effective ultrasonic excitation. As shown in Figure 2, the Nd:YAG source laser beam is focused using a Lak10 focusing lens with a focal length of 15 mm before entering the SubMiniature version A (SMA) connector. Then, the laser beam exiting from the SMA at the other end of the fiber travels through a metal tube, and the light is focused again using the identical Lak10 lens. A tube made of stainless steel and aluminum is inserted between the SMA and the focusing lens to minimize the heat transfer from the specimen to the SMA connector. As a final step, a stainless steel strip is used to fix the focusing module to the specimen.

**Optical fiber–guided laser ultrasonic sensing**

Figure 3 shows the detailed configuration of the optical fiber–guided laser ultrasonic sensing component. This study utilizes a phase-modulation fiber-coupled laser Doppler interferometer (OFV-551; Polytec) to measure the out-of-plane ultrasonic response of the pipe surface since it is more sensitive and stable than conventional intensity-modulation interferometers.\textsuperscript{22} The fiber
interferometer normally uses a continuous wave (CW) laser as a power source, and its power level is much lower than an excitation laser. The interferometer in this study uses a He–Ne continual laser source with 633 nm wavelength, 15 W maximum power, and 16 \textmu m beam size. When a continuous laser beam is pointed at a vibrating object and scattered back from it, the velocity of the vibrating object produces a phase shift of the laser beam due to the Doppler effect. The frequency modulation of the Doppler signal recovers the velocity.
information, and the phase modulation reconstructs the displacement.\textsuperscript{23,24}

Since the laser beam emitted from the fiber interferometer is less powerful than the pulsed excitation laser beam, a panda-type single mode fiber is used for the transmission of the sensing laser beam. The sensing fiber is made of polarization maintaining (PM) fiber, which can reduce the power loss induced by the polarization direction. This polarization-induced power loss is more critical for the sensing laser beam than the excitation beam, since the power loss directly governs the signal-to-noise ratio of response signals and it cannot simply be enhanced by raising the laser power level. Since the response signals contain background noise and multimodal complexity from the pulse input, the measured responses are amplified with a gain of 10 and band-pass filtered in a range of 10–300 kHz using a low-noise amplifier (SR560; Stanford Research Systems).

In order to enhance the transmission of the incident and reflected laser beams, a sensor head is inserted at the end of the optical fiber. A Lak10 focusing lens with a focal length of 15 mm is inserted close to the target surface similar to the previous case in section “Optical fiber–guided laser ultrasonic generation.” One difference from the previous wave generation component is that an additional KG1 filter is placed close to the sensor head to prevent the infrared heat radiation from the heated pipe to the sensor head. Furthermore, the fixture strip and metal tube identical to the previous wave generation component are used.

**Baseline-free damage detection technique**

In this section, a damage detection algorithm specifically tailored to the proposed laser ultrasonic system is developed for pipe monitoring. There is a rich volume of ultrasonic techniques developed for pipeline monitoring. Some researchers have excited axisymmetric wave modes, $L(0,1)$ or $T(0,1)$, and then extracted non-axisymmetric and mode-converted flexural modes, $F(m,n)$, induced by structural defects.\textsuperscript{25–28} Other researchers have developed beam-forming techniques to steer ultrasonic waves for selective inspection of a desired point in a pipe.\textsuperscript{29,30} Based on a time reversal concept, images of detects in pipes are constructed by exciting $L(0,1)$ and sensing $F(m,n)$ modes.\textsuperscript{31}
There are challenges in using these conventional damage detection techniques in conjunction with the proposed laser ultrasonic system. The proposed laser system applies a broadband pulse input only to limited discrete excitation points and simultaneously generates multiple nonaxisymmetric modes. Therefore, it cannot selectively excite axisymmetric wave modes to extract mode-converted flexural modes induced by structural defects. Also, the waveform that the proposed system can generate is limited only to a pulse input, and time-delayed multichannel excitation is difficult using the proposed system. That is, the aforementioned beam-forming and time reversal techniques cannot be used with the proposed laser ultrasonic system. Therefore, a new damage detection algorithm developed and tailored specifically for the proposed optical fiber–guided laser ultrasonic system is presented below.

Figure 4 shows the configuration of ultrasonic wave generation and sensing used for the proposed damage diagnosis. For ultrasonic wave generation, multiple laser excitation points (group A: \( A_1, A_2, \ldots, A_n \)), equally spaced in a circumferential direction, are placed at one end of the pipe. Similarly, multiple laser sensing points (group B: \( B_1, B_2, \ldots, B_n \)) are positioned at the other end of the pipe. Here, \( n \) is the number of excitation points (or the sensing points), and this number can be increased to improve the spatial resolution of damage detection. In a round-robin manner, ultrasonic waves are generated and measured from different pairs of excitation and sensing points.

Figure 5 shows several groups of identical signals based on the axisymmetric nature of the intact pipe. The pipe in Figure 5 is shown unwrapped for an illustration purpose. Due to the axisymmetric nature of the pipe, ultrasonic wave signals with the same pitch–catch distance should be, in theory, identical for the intact condition. The followings are examples of signal groups with the equality.

(a) \( \text{Signal } A_1B_1 = \text{Signal } A_2B_2 = \cdots = \text{Signal } A_{n-1}B_{n-1} = \text{Signal } A_nB_n; \)
(b) \( \text{Signal } A_1B_2 = \text{Signal } A_2B_1 = \cdots = \text{Signal } A_{n-1}B_{n-1} = \text{Signal } A_nB_{n-2}; \)
(c) \( \text{Signal } A_1B_3 = \text{Signal } A_3B_1 = \cdots = \text{Signal } A_{n-2}B_{n-2} = \text{Signal } A_nB_{n-2}; \)

The basic premise of the proposed damage detection algorithm here is that this equality breaks down when a nonaxisymmetric defect is introduced. Note that there are other pairs of identical signals with the same pitch–catch distance depending on the size of \( n \).

Based on this observation, the following damage index (DI) can be computed in a round-robin fashion

\[
DI(i,j) = 1 - \max \text{corr}(f_i,f_j) \tag{1}
\]

\[
\max \text{corr}(f_i,f_j) = \max_i \left\{ \frac{1}{N-1} \sum_{j=0}^{N-1} (f_i(t+j) - \bar{f}_i)(f_j(t) - \bar{f}_j) \sigma_f \sigma_f \right\} \tag{2}
\]

In equations (1) and (2), \( f_i \) and \( f_j \) are the time response signals obtained from two wave paths with the identical travel distance; \( \bar{f}_i \) is the mean of \( f_i; \sigma_f \) is the standard deviation of \( f_i; \) \( N \) is the total number of data points in \( f_i; \) and \( t \) is the time shift. Therefore, all the DI values will be close to zero for an intact case, but DI values for certain pairs of \( f_i \) and \( f_j \) will increase when there is a nonaxisymmetric defect in the pipe.

After computing all DI values, a sequential outlier analysis with an adaptive threshold value \( \eta^* \) is performed to identify the DI values that are obtained from the wave paths passing through a structural damage
and much larger than the ones obtained from the intact paths. The procedure of the proposed sequential outlier analysis shown in Figure 6 can be described as follows:

1. Arrange all DI values in an ascending order ($1 \leq m \leq N$).
2. Fit a parametric distribution function up to the $m - 1$ smallest DI values and compute a threshold corresponding to a user-specified one-sided confidence level. Initial $m - 1$ is typically selected to be the half of all available combinations defined in equation (2).
3. If the $m$th smallest DI value is larger than the threshold value, the wave paths corresponding to all the $m$th smallest DI and the larger DI values are determined to pass through a defect location. If not, repeat steps 2 and 3 for the next smallest DI value $m + 1$, until it reaches $N$. If all the DI values are below the threshold value, the pipe is intact.

Figure 5. Group of equal signals based on the axisymmetric nature of the intact pipe: (a) equality among Signals $A,B$, (b) equality among Signals $A_{i-1}$ and Signals $A_{i+1}$, and (c) equality among Signals $A_{i-2}^2$ and Signals $A_{i-2}^2$. Note that the pipe is shown unwrapped for a demonstration purpose here.
Because the DI values are bounded between 0 and 1, the following β distribution is used to describe the statistical distribution of the DI values:

\[ f(x; \alpha, \beta) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1 - x)^{\beta-1} \]  

where \( B(\alpha, \beta) \) is the Beta function; \( \alpha \) and \( \beta \) are the shape parameters. A goodness-of-fit test using the Kolmogorov–Smirnov (K-S) test confirms that the β distribution properly describes the population of the DI values obtained from the intact conditions. The threshold value is set to the one-sided 99.7% (3σ) confidence level.

**Experimental results**

**Experimental description**

Figure 7 shows the overall configuration of the experimental setup. The test is designed to simulate structural and operational conditions of a typical secondary coolant system in NPPs. The target specimen (Figure 8) is a stainless steel seamless-typed pipe (KS D 3562) commonly used for high-pressure piping systems in NPPs. The outer diameter of the pipe is 114.3 mm and the wall thickness is 6 mm. The axial length of the target specimen is 1000 mm, and the distance between ultrasonic wave generation and sensing points is set to 300 mm.
As for structural damage, a longitudinal notch is engraved 575 mm away from the left end of the pipe to simulate a longitudinal crack. The notch is 20 mm long, 2 mm wide, and 2 mm deep.

In this experiment, there are four excitation points 350 mm away from the left end and four sensing points 350 mm away from the right end. Because there are four equally spaced excitation points in the circumferential direction (as well as sensing points), possible wave path groups become as follows: (a) 6 pairs for Signals $A_iB_i$ ($4C_2$); (b) 28 pairs for Signals $A_iB_{i+1}$ and $A_{i-1}B_i$ ($8C_2$); and (c) 6 pairs for Signals $A_iB_{i+2}$ and $A_{i-2}B_i$ ($4C_2$). Therefore, there are a total of 40 wave path pairs and 40 DI values ($N = 40$).

Baseline-free damage diagnosis

Figure 9 shows how several representative signals change from the intact (dotted line) condition to the damage (solid line) one. Each response signal is normalized by subtracting the mean and dividing by the standard deviation for better comparison. Then, the maximum correlation ($\text{max corr}$) between the intact and damage cases is computed using equation (2) for each signal as follows: 0.8849 for Signal $A_2B_2$; 0.6527 for Signal $A_3B_2$; 0.2668 for Signal $A_1B_2$; and 0.6080 for Signal $A_4B_2$. Because Signal $A_3B_2$ goes directly through the introduced longitudinal notch, the maximum correlation for this path changed most drastically. However, it should be noted that the actual damage diagnosis proposed in this study is performed without this type of pattern comparison with the previously obtained intact signals.

Figure 10 shows the result of the sequential outlier analysis for the damage case. Here, the DI values in the $y$-axis are sorted in an ascending order and the indices for the corresponding pairs of wave propagation signals are shown in the $x$-axis. For the outlier analysis of the $m$th DI value, a $\beta$ distribution is fitted to the $m-1$ smallest DI values and a threshold value (the dotted line) corresponding to a one-sided 99.7% ($3\sigma$) confidence level of the $\beta$ distribution is instantaneously computed. This process is repeated from $m = 20$ to 40. Note that $m$ started from 20 ($= N/2$) with the assumption that the target defect is localized and at least the half of the DI values are not affected by the defect.

Among all DI values obtained from the damage case, seven DI values associated with Signal $A_3B_2$ became noticeably larger than the other DI values. This observation indicates that Signal $A_3B_2$ is drastically different from the other response signals due to the existence of a structural defect along this path. Even though some other response signals are more or less influenced by the notch, Signal $A_3B_2$ is far more affected by the defect than the other signals because this signal directly passes through the defect.

Figure 11 shows the result of the sequential outlier analysis performed for the intact case to check whether the proposed damage detection technique is vulnerable to a false alarm. As shown in Figure 11, no false alarm is triggered in this particular example.

Effect of insulator

The majority of pipes in NPPs are covered with insulators to prevent too much heat flow to the air. An actual insulator commonly used in NPPs is employed here, and the particular insulator used in this study is composed of two layers: a 50-mm inner layer made of glass wool and a 20-mm outer layer made of glass felt. Also, it is designed to bring down temperature from 300°C at the pipe surface to 40°C at the outer insulator surface. The effect of the insulator on response signals is examined in Figure 12. The dotted line indicates the response signal with the insulator and the solid line without the insulator. The comparison of these two signals reveals a marginal effect of the insulator.
Figure 9. Comparison of the response signals obtained from the same pitch-and-catch distance and direction: (a) Signal A$_2$B$_2$, (b) Signal A$_4$B$_4$, (c) Signal A$_3$B$_2$, and (d) Signal A$_5$B$_2$. Dotted and solid lines are obtained from the intact and damage cases, respectively. Here, the "max corr" is computed between the intact and damage case signals.

Figure 10. Sequential outlier analysis for the damage case. DI: damage index.
Next, the effect of temperature on the proposed optical fiber–guided laser ultrasonic system is investigated. For typical NPPs, the nominal operational temperature of the secondary coolant system is approximately 300°C near the reactor, and the temperature is maintained around 100°C–200°C in the secondary coolant system. To control the temperature of the test specimen, a temperature controller specially designed by SKI Corporation is used (Figure 13). The controller has a built-in pipe and a thermal conductor inside the pipe to heat up the pipe. The axial length of the pipe is 600 mm, the outer diameter is 114.3 mm, and the thickness is 3 mm. The wave propagation distance between the wave generation and sensing points is set to 300 mm, which is same as the previous experiment. When the pipe is heated and the pipe surface temperature is stabilized at 300°C, the temperatures of the first and second layers of the insulator are 48.7°C and 41.2°C, respectively, demonstrating the effectiveness of the insulation layer.

Figure 14 shows the response signals obtained from the pipe specimen at varying temperatures. The temperature was increased from the room temperature to 300°C, and the response signals are measured from 100°C to 300°C at an interval of 50°C. As the temperature increases, the peak amplitude of the signal decreases and the response is delayed in the time domain. Note that the amplitude and the arrival time of the response signal are 3.395 mV and 0.1214 ms, respectively, at 100°C. However, these values change to 2.981 mV and 0.123 ms at 200°C, and 2.249 mV and 0.1252 ms at 300°C, respectively. The attenuation and time delay are mainly caused by the reduction of Young’s modulus due to the increase in temperature.35

Because significant response signal changes can be observed due to temperature even without any structural defects, a proper measure needs to be taken for reliable damage diagnosis. To compensate the signal changes induced by temperature variations, a baseline subtraction method has been proposed for damage detection.36 This method identifies damage by subtracting the test signal from the baseline signal after...
correcting effect of temperature on group velocities of specific wave modes. However, this technique cannot be applied to the proposed optical fiber–guided laser ultrasonic system because a broadband pulse input used in the proposed system excites multiple wave modes simultaneously and temperature compensation of all these modes is practically impossible. On the other hand, the proposed damage detection algorithm can be effectively used even under varying temperature conditions since the axisymmetric nature, which should hold for the intact case, is irrelevant to temperature changes and wave frequency ranges. The axisymmetric nature is broken down only when a nonaxisymmetric defect is introduced. However, large nonaxisymmetric temperature gradient could also cause false alarms.

Conclusions

This study develops an optical fiber–guided laser ultrasonic system and a baseline-free damage detection technique specially designed for SHM of insulated pipes under high-temperature environment in NPPs. An optical fiber with a specially designed focusing lens and a fixture are used to deliver a Nd:YAG pulse laser to an embedded target excitation point for ultrasonic wave generation. Another optical fiber is connected between a fiber vibrometer and a sensing measurement point for ultrasonic wave sensing with a similar focusing lens and a fixture. The proposed system allows generating and measuring ultrasonic waves at any desired locations even when they have limited accessibility due to the insulators or high-temperature environment. The performance of the proposed system has been successfully demonstrated at varying temperatures up to 300°C. A baseline-free damage detection algorithm is developed along with the laser system based on the axisymmetric nature of multiple wave propagation paths in pipes. The axisymmetric nature is valid for the intact pipe, but it breaks down when a nonaxisymmetric defect is introduced. The robustness of the proposed baseline-free damage detection technique has been experimentally verified both for the intact and damage cases of a pipe specimen commonly used in NPPs.

Several follow-up studies are required to improve the performance of the proposed system. First, a radiation hardening test on the proposed measurement system is necessary for the system installation in real NPPs. In fact, we designed the proposed optical fiber–guided laser ultrasonic system by carefully choosing radiation-proof components, and a radiation hardening test to prove its robustness against radiation exposure is underway. Second, an optical switching device should be incorporated to the proposed system for selective ultrasonic generation and sensing at multi-channels. Third, the proposed damage detection algorithm is applicable only to a simple straight pipe. Further research is warranted to explore damage detection in more complex pipe geometries. Finally, the proposed approach is only intended for damage identification. Therefore, once damage is detected, additional measures should be taken for detailed damage quantification.

Funding

This research was supported by Mid-career Researcher Program and National Nuclear R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2011-0016470 and No. 2011-0018430) and by the Innovations in Nuclear Power Technology (Development of Nuclear Energy Technology) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Knowledge Economy (No. 2010T100101057) in Korea.

References


