Laser Based Structural Health Monitoring for Civil, Mechanical and Aerospace Systems

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ABSTRACT

This paper provides an overview of ongoing laser ultrasonics based structural health monitoring (SHM) activities being performed by the author. Particular focus is given to (1) the development of a fully noncontact laser ultrasonic system that can easily visualize defects with high spatial resolution, (2) laser based wireless power and data transmission schemes for remote guided waves and impedance measurements, (3) minimization of false alarms due to varying operational and environmental conditions, and (4) extension to embedded laser ultrasonic excitation and sensing. SHM examples ranging from bridges to airplanes, as well as nuclear power plants, high-speed rails and wind turbines are also presented.

Keywords: laser ultrasonics, structural health monitoring, nondestructive testing, ultrasonic imaging

1. INTRODUCTION

There have been increasing demands to better safeguard civil, mechanical and aerospace systems via structural health monitoring (SHM) technology. In particular, ultrasonic based SHM techniques are popular because ultrasonic waves are sensitive to even small defects and can travel a relatively long distance with little attenuation[1-6]. However, the conventional ultrasonic techniques, which rely on contact transducers, suffer from the following problems: (1) Ultrasonic excitation and sensing points are limited only at several discrete points, resulting in low spatial resolution; (2) Transducer installation and cabling are typically very time consuming and labor intensive; (3) Often the transducers become the weakest link in the entire system, potentially increasing the maintenance costs; (4) Most contact transducers are not applicable under harsh environments such as high temperature and radioactive conditions; and (5) For certain applications, contact transducers can alter the dynamic characteristics of target structures.

Therefore, there is a strong desire to adopt noncontact laser ultrasonic techniques, which have been extensively studied by the nondestructive testing community, to SHM applications. For example, ultrasonic waves can be generated by using pulse[7-13] and continuous laser[14,15], and the corresponding responses can be measured by using laser interferometry[16-20]. Using the measured responses, ultrasonic wave propagation is visualized and various types of defects in metal and composite structures can be detected[13,18-20]. Noncontact laser ultrasonic techniques can provide the following advantages: (1) Ultrasonic wavefield images with high spatial resolution can be obtained, making subsequent damage diagnosis much intuitive and easier; (2) Damage diagnosis can be performed without using baseline data obtained from the pristine condition of the target structure, enabling the scanning techniques to be less vulnerable to false alarms due to changing environmental and operational conditions; and (3) Because no transducer or only a few transducers need to be placed on target structures, noncontact techniques can be rapidly deployed.

In this study, a complete noncontact laser scanning system is developed for ultrasonic excitation and sensing, and a novel image processing technique is proposed for automated damage visualization and diagnosis. The laser ultrasonic scanning system is developed by integrating a Q-switched Nd:Yag pulse laser for ultrasonic generation, a laser Doppler vibrometer (LDV) for ultrasonic measurement and galvanometers with focal lenses for laser scanning. The developed laser scanning system allows scanning of both ultrasonic excitation and sensing laser beams, thus making it possible to scan a large surface. Second, laser based power and data transmission techniques are developed so that ultrasonic waves can be generated and measured using a combination of piezoceramic transducers and laser. Third, an embeddable ultrasonic sensing system is developed based on the same principle of noncontact laser ultrasonics especially for high temperature and radioactive environments. Finally, applications of laser ultrasonics to various civil, mechanical and aerospace systems are presented.

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2. WORKING PRINCIPLES OF LASER ULTRASONICS MEASUREMJENT SYSTEMS

2.1 Noncontact Laser Ultrasonic Excitation and Sensing

When a high power laser beam is focused to an infinitesimal area, the thermal expansion of the area creates ultrasonic waves. Typically, a Q-switched Nd:Yag pulse laser is used for ultrasonic generation, and it is combined with a focal lens and scanning mirror. Here, the power level, laser pulse duration and laser beam size need to be carefully tailored because a focused high laser beam above a certain threshold can cause surface melting, vaporization, ablation and plasma formation[7].

Most commercially available laser vibrometers measure the out-of-plane velocity of a target specimen based on the Doppler frequency-shift effect of lights[21]. It is based on a heterodyne scheme which extracts the frequency-shifts from the interference between a reference laser beam and a reflected laser beam from a vibrating target surface[7]. Here, the sensitivity of the sensing laser heavily depends on the surface condition of the sensing points and the incident angle of the sensing laser beam over the scan area. For example, a polished surface is advantageous when the sensing laser beam is perfectly perpendicular to the target surface because the majority of the incident laser beam is reflected straight to the receiver. However, when the incident angle increases, the returned beam intensity along the incident angle decreases. Therefore, a retroreflective tape or special coating is often applied to the sensing surface to increase the light intensity of the backscattered laser beam along the incident angle and to improve the LDV sensitivity.

Based on the linear reciprocity of ultrasonic waves[22,23], it can be easily shown that an ultrasonic signal excited by a pulse laser at point A and measured by a sensing laser at point B is identical to the one excited by the same pulse laser at point B and measured by the identical sensing laser at point A. Therefore, ultrasonic scanning can be achieved by scanning either the excitation or sensing laser beams. However, scanning the excitation laser beam is often more effective than moving around the sensing laser beam particularly for curved surfaces or large scan areas because the ultrasonic generation by a pulse laser beam is little affected by the surface irregularity and the incident angle of the excitation laser beam. Typically, the allowable incident angle for an excitation laser is up to ±70° while ±20° for a sensing laser [7, 13]. Major concerns with pulse laser excitation are that (1) the waveform is limited only to a pulse and (2) the high power laser can damage the painting and/or coating layer of the specimen as well as the specimen itself. To address these issues, a unique combination of piezoceramic transducer and laser is introduced in the following subsection for a different type of remote ultrasonic excitation and sensing. A schematic of the full noncontact laser system built by the author's research group is shown in Figure 1.

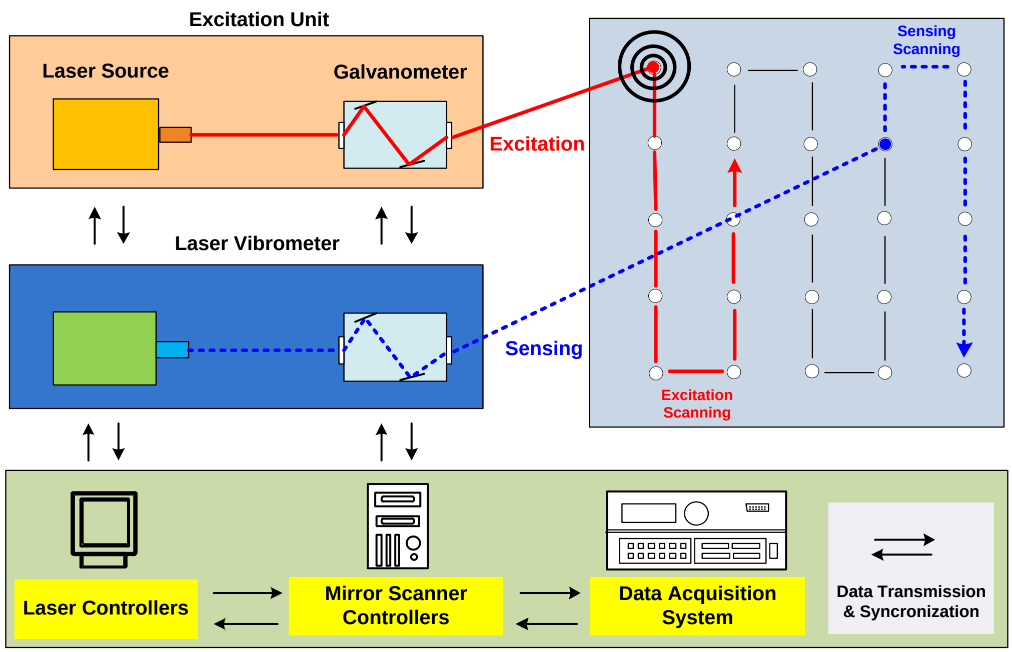


Figure 1. An overall schematic of the complete noncontact laser ultrasonic scanning system becomes of a Nd:Yag pulse laser, a laser Doppler vibrometer, scanning mirrors, and a controller.

2.2 Laser based Piezoceramic Transducer Excitation and Sensing

Figure 2 shows an overall schematic of the wireless ultrasonic excitation and measurement system composed of the data interrogator, laser beams, PZT excitation and sensing nodes[24]. At the data interrogator, an arbitrary waveform such as a windowed sine signal is generated and converted into a laser beam using a laser diode, and the laser beam is wirelessly transmitted to the photodiode in the PZT excitation node. Then, the laser beam is converted back to an electric signal by the photodiode and excites the PZT attached on a structure. Subsequently, the excited PZT creates ultrasonic waves within the structure. The guided waves generated by the excitation PZT are transmitted through the structure, and measured by the sensing PZT. The process of wireless data transmission in the PZT sensing node is similar to that of wireless power transmission in the data integrator. That is, the measured electric signal is converted into a laser light in the PZT sensing node and transmitted back to the other photodiode located in the data interrogator for signal processing. Note that, because the response signal is often weak, the extra power necessary for converting the response electric signal to a laser at the PZT sensing node is augmented by a separate high power laser. More details can be found in the previous work of the author's research group[24].

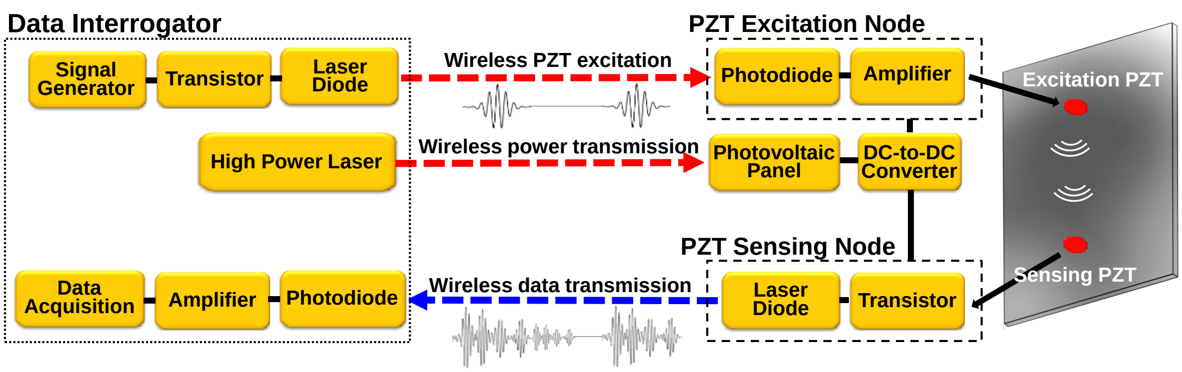


Figure 2. An overall schematic of the proposed optics-based wireless guided wave measurement system (▬: wired electric connection, ▬➔: wireless laser) [24]

3. CIVIL, MECHANICAL AND AEROSPACE APPLICATIONS

3.1 Aircraft Applications

In this section, wavefields obtained from a composite plate with an internal delamination are visualized using an LDV and a PZT transducer. The composite plate shown in Figure 3 was subjected to an impact, and the formation of an internal delamination near the center of the plate was confirmed from nondestructive thermographic imaging. The 3 cm long damage area could be seen on the back side of the plate (Figure 3), but on the front (impacted) side there was only a small dent, barely visible to the naked eye. A piezoelectric wafer transducer was used to generate guided waves at a single point within the test article, and the corresponding responses were measured by a LDV. The data was then exported to a data acquisition system and processed. The snapshots at three representative time instants are shown in Figure 4. All images are plotted in RGB scale where low to high values are mapped from blue to red with green indicating middle range values. In Figure 4(a), the incident waves can be clearly seen, and the interaction with the delaminated area is apparent in Figure 4(b). Ultrasonic oscillations at the delamination location can be observed long after the incident waves had passed the delaminated area (Figure 4(c)). Figure 5 shows the time sequenced wavefields when the originally measured wavefield images in Figure 4 are passed through the standing wave filter. In Figure 5(b), standing waves can be observed at the delamination location. Although mitigated, standing waves are found to be present long after the incident waves have passed (Figure 5(c)). Notice that the incident waves are filtered out in Figure 5. More details on this experiment can be found in the previous work of author's research group[19] and similar testing were conducted for more realistic composite structures with additional structural features and metallic structures as well.

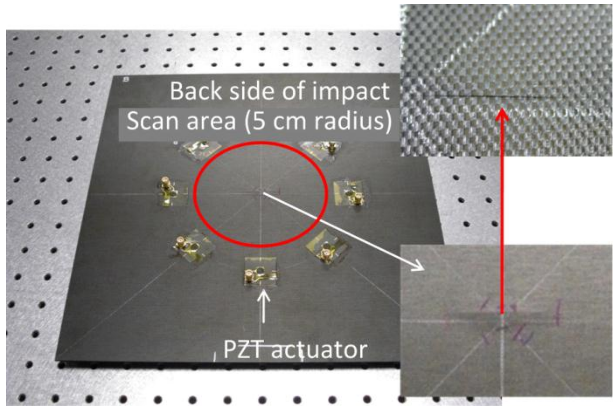


Figure 3. A multi-layer composite plate with impact-induced delamination

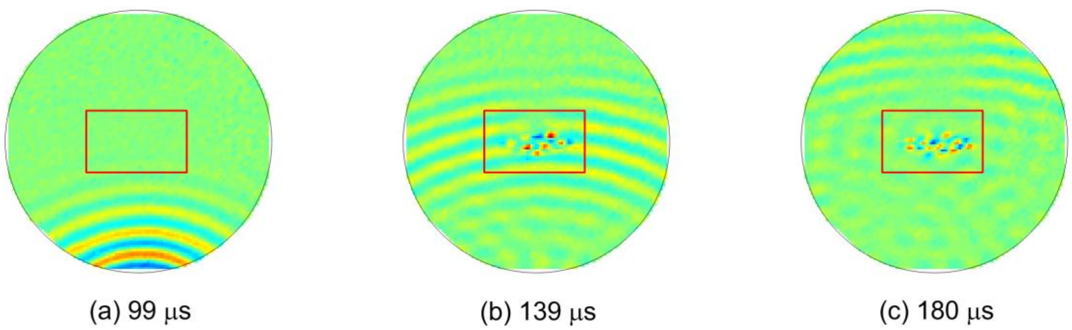


Figure 4. LDV imaging of Lamb wave propagation in a 1.8 mm thick graphite plate containing delamination. Standing waves are observed at the delamination site.

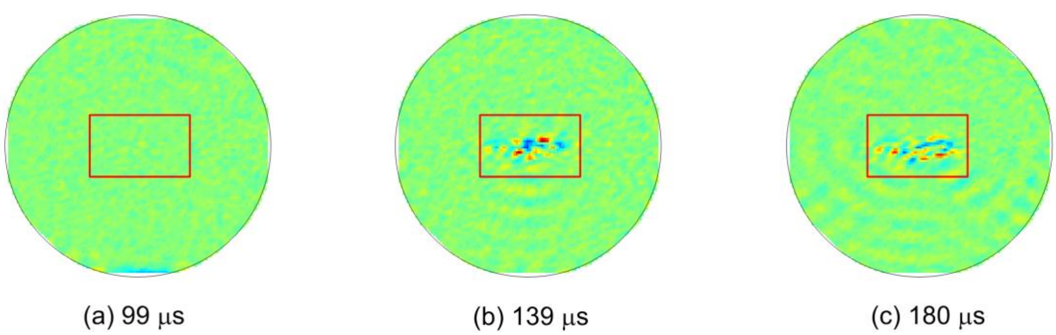


Figure 5. Isolating the standing wave components from the velocity fields in Figure 4

3.2 Wind Turbine Applications

In this application, the laser ultrasonic imaging technique is further advanced so that wavefield images can be constructed from a rotating blade using an embedded piezoelectric sensor and a scanning excitation laser system. Here, the biggest challenge is to precisely estimate and control the exact excitation point when the wind blade is rotating with additional ambient vibration and having complex shapes. Instead of precisely controlling the excitation laser beam, its position is roughly controlled by the existing galvanometer and the exact position is estimated by using the impact localization technique previously developed by the author's research group[25]. The overall procedure is shown in Figure 6. First, training ultrasonic signals are measured at the fixed sensing point by scanning the excitation laser over the target surface of the blade when the blade is in a stationary condition. Once the training is complete, an ultrasonic signal is generated for the rotating blade using the excitation laser and measured by the sensor. The correlation between the measured response and a training response is maximized when they correspond to the same excitation point. Finally, ultrasonic images are generated by scanning the excitation laser over the target surface of the blade. The effectiveness of the proposed imaging technique is investigated through experimental tests performed on a rotating blade specimen shown in Figure 7. Training was performed for the 5 cm by 12 cm rectangular area shown in in Figure 7(b), and the ultrasonic images were constructed for the 4 cm by 4 cm square area within the trained region. The blade was rotating at 20 rpm when the scanning was performed, and a notch (20 mm X 2 mm X 0.5 mm) was introduced on the back side of the specimen. The final ultrasonic images captured in step (6) of Figure 6 properly indicated the appearance of the crack. More detailed on this experiment can be found in the previous work of the author's research group[26].

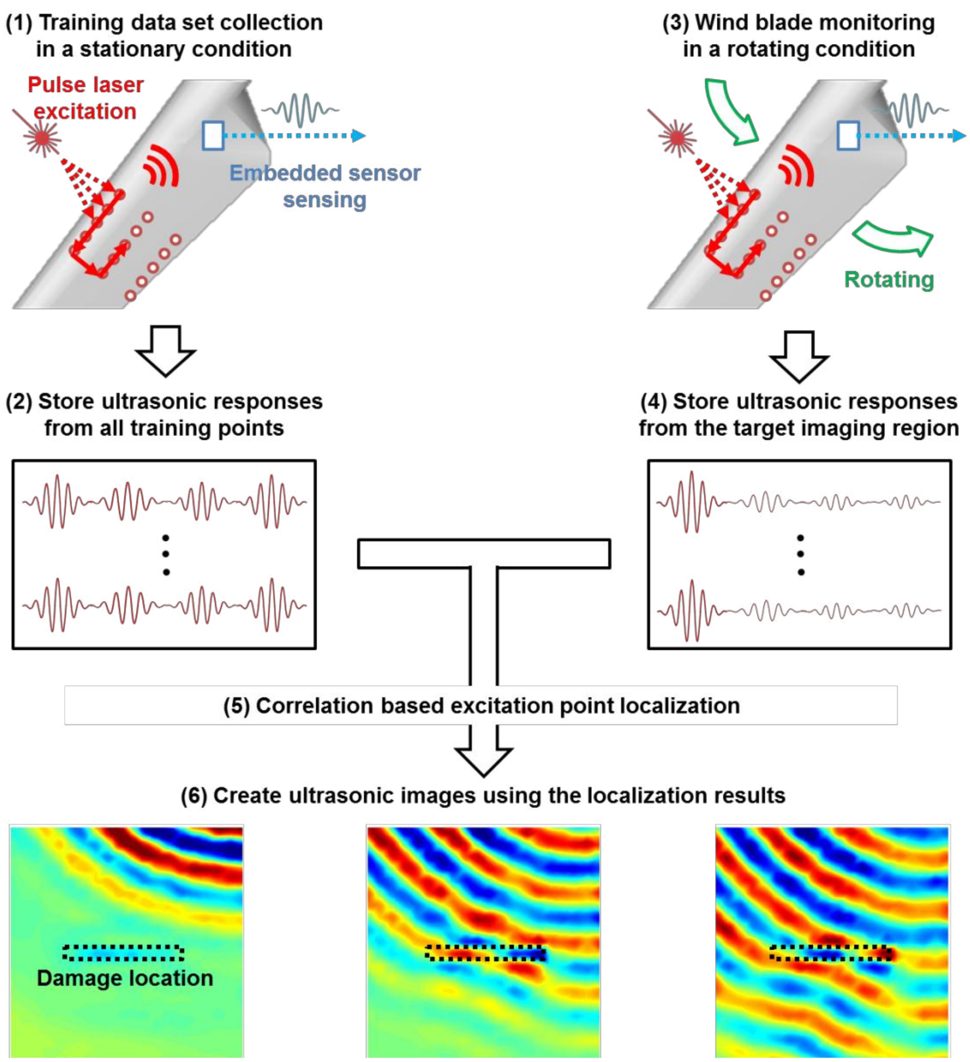
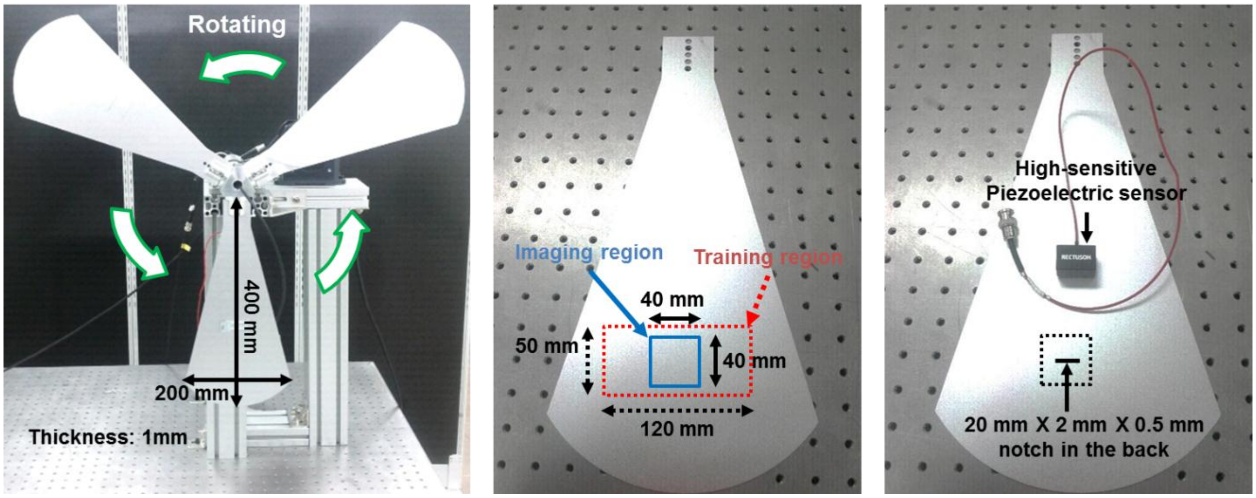


Figure 6. Overall scheme of the proposed laser ultrasonic imaging technique for a rotating blade. To collect training data, in Steps (1) and (2), ultrasonic waves are obtained by generating ultrasonic waves using a pulse laser excitation and measuring response using the embedded sensor, covering the entire training area by scanning the laser beam. In the wind blade

monitoring stage, the pulse laser shoots the laser beam when the target object rotates a single turn. The corresponding ultrasonic wave is measured by the embedded sensor and collected in step 3. Step 3 is repeated for the entire target area (Step 4). The exact ultrasonic generation location is identified through correlation analysis between the training data and the measured signal in Step 5 and ultrasonic images are constructed using the measured signals and corresponding localization results (Step 6).



(a) A small scale wind blade model

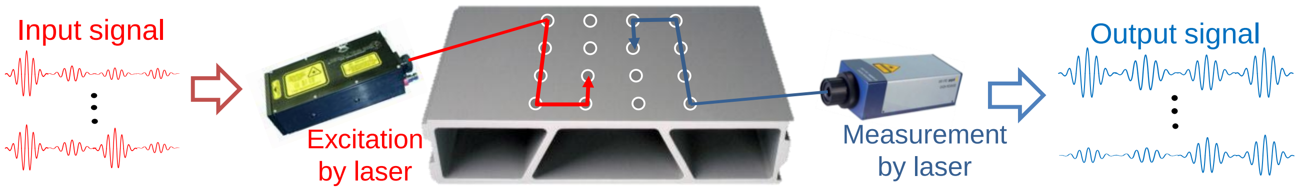
(b) Front side of the blade

(c) Back side of the blade with sensor installation

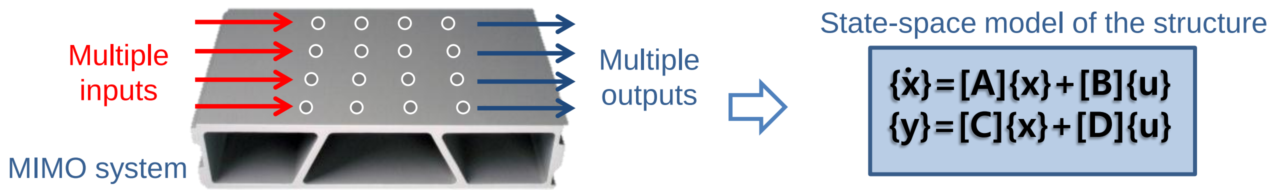
Figure 7. An aluminum wind blade model with a piezoelectric sensor installed at the back side of the blade. The black dotted box and the black solid box in (b) indicates the training region and the imaging region, respectively.

3.3 Bridge Application

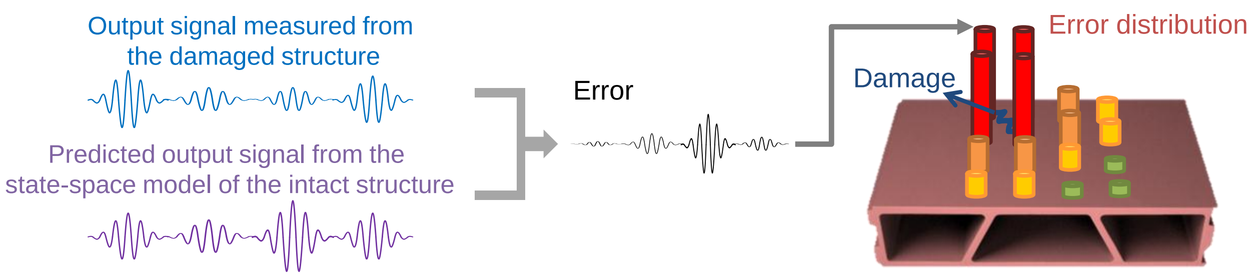
A similar laser scanning has been performed for a real bridge in South Korea. In this example, the scanning was performed from the outside surface of the steel box girder to detect hidden crack inside the girder. Furthermore, the combination of a PZT transducer and laser described in Section 2.2 was used for ultrasonic excitation rather than a pulse laser excitation[27]. We also plan on using a LDV and a modal shaker together for system identification. According to the recently developed subspace system identification technique[28], the physical parameters of a structural system such as mass, damping and stiffness matrices can be estimated directly from measured data if the input force(s) and corresponding displacement responses can be measured. Currently, we are conducting a preliminary experiment with a simple cantilever beam to verify this postulation. We also intend to adopt the concept of subspace system identification to local ultrasonic system identification shown in Figure 8. By scanning both the excitation and sensing lasers simultaneously, we can build a multi-input and multi-output state-space model and use it for damage localization. For example, if the error between the actual measurement and the prediction from the state-space model increases at a specific location in the future, the damage is most likely near the area. Then, we can perform more detailed ultrasonic scanning just for this area with higher spatial resolution. Through this combination of low and high resolution scanning, we can significantly reduce the scanning time required for large test structures.



(a) Multi-input and multi-output data measurement using scanning excitation and sensing lasers



(b) State-space model estimation using subspace system identification



(c) Damage localization using state-space model

Figure 8. Local ultrasonic system identification for low-resolution estimation of a damage area

3.4 High Speed Train Applications

Our laser related research for high speed trains is composed of (1) monitoring of a bogie system and (2) real-time rail inspection. The first application shown in Figure 9 is to monitor the bogie system when the train comes in to the inspection station. Here, the idea is to install only PZT and FBG sensors to the bogie and use laser and a single optical fiber to excite the PZT and retrieve the response signal from the FBGs. Then, data analysis will be performed by the off-site data acquisition station. The integrated PZT/FBG using a common laser source and optical cable is illustrated in Figure 10[29]. First, a tunable laser, which is used as a common power source for both guided wave generation and sensing, is modulated using an optical modulator in accordance with a desired waveform created by an arbitrary waveform generator (AWG). 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 excitation 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. Then, a PZT transducer is excited, and guided waves are generated in a test structure. Next, the laser beam passes through an optical circulator that links the laser beam, 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 the propagating guided waves. Eventually, the segments of the optical fiber represented by dashed lines in Figure 10 will be removed, and the laser beams will be wirelessly transmitted, allowing the installation of only the PZT transducer and FBG sensor on the bogie system. A good agreement between ultrasonic signals obtained by the proposed PZT/FBG hybrid system and a conventional measurement system is shown in Figure 11.

The second application is to mount a noncontact laser ultrasonic device to a moving train and use it for real-time rail inspection. Current state-of-art studies often use a Nd:Yag pulse laser for generating ultrasonic waves on rail surfaces and an air-coupled transducer for measuring the corresponding ultrasonic response leaking from the rail surface apart from the generation point. One of the main problems with the current approaches is that the stand-off distance between the rail surface and the air-coupled transducer is limited only to 1 or 2 cm. To increase the stand-off distance, we are exploring the possibility of using a specially designed LDV for ultrasonic wave measurement instead of the air-coupled transducer. To achieve this, we are focusing on addressing the following two issues: (1) How to separate high-frequency and small-amplitude out-of-plane ultrasonic components from low-frequency and large-amplitude rail vibrations in both horizontal and vertical directions and (2) How to minimize speckle noises when the train is moving.

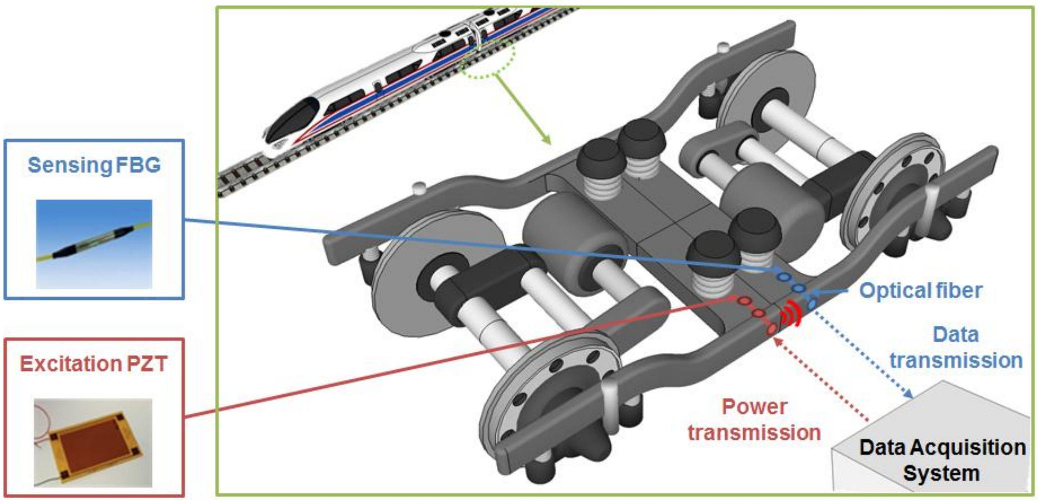


Figure 9. Monitoring of high-speed train bogie using embedded hybrid sensors and laser power/data transmission

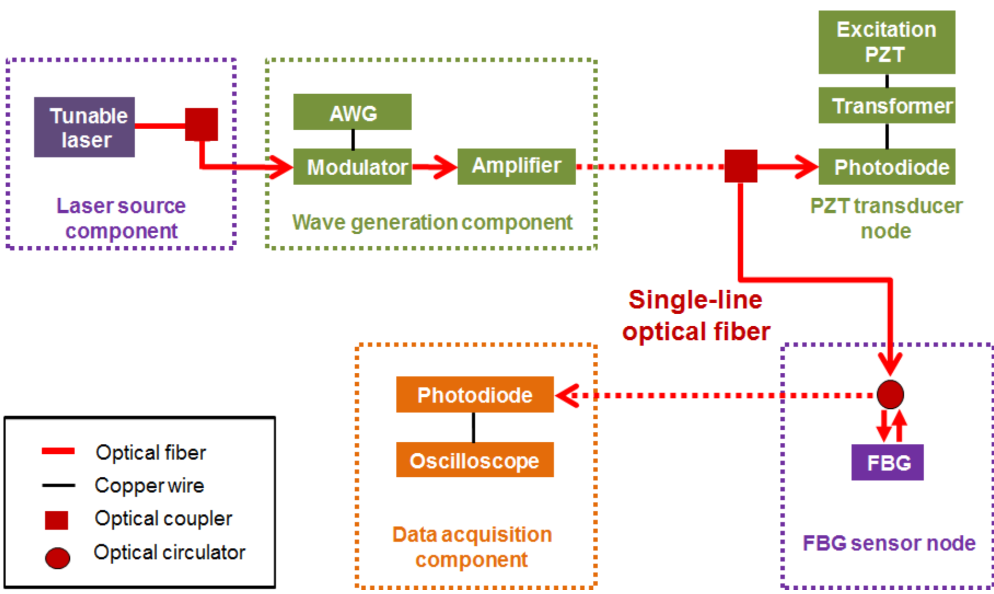


Figure 10. Integrated guided wave generation and sensing using a single laser source and optical fiber

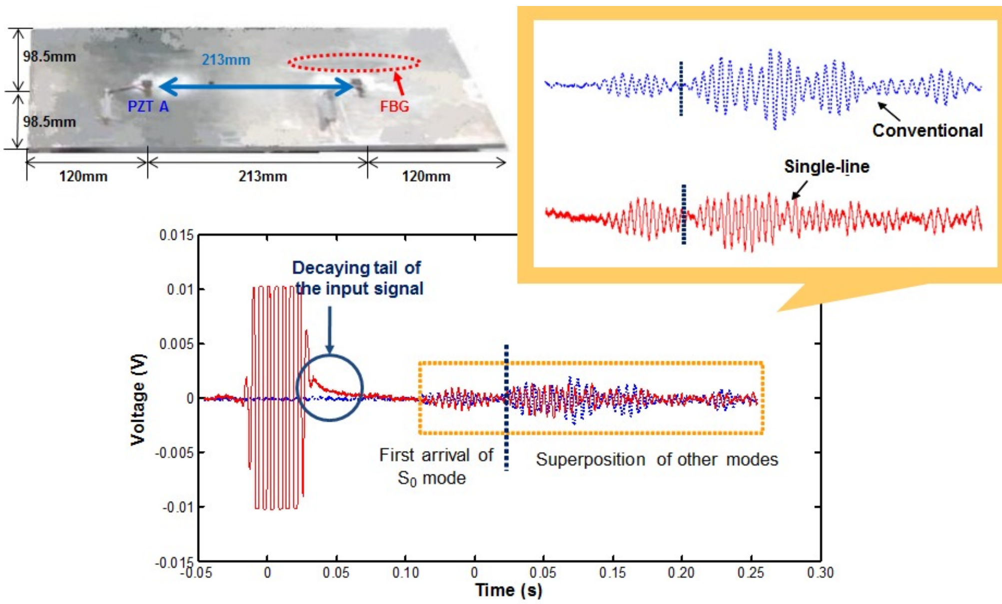


Figure 11. Comparison of ultrasonic signals obtained by the proposed PZT/FBG hybrid system (solid line) and the conventional measurement system (dotted line)

3.5 Nuclear Power Plant (NPP) Applications

To meet fast-growing power demands, nuclear energy has drawn attention as one of the alternative energy sources. However, it has been reported that many NPPs continue to deteriorate due to their structural aging. Among all operational NPPs worldwide, 78% have been in operation over 20 years and 30% over 30 years[30]. Furthermore, public concern over the safety of NPPs is continuously growing. Many countries are facing growing public opposition to the construction and operation of NPPs and under a great deal of pressure to shut down existing NPP facilities. In response to the public concern, nuclear regulatory authorities in many countries have tightened their safety measures and established strict inspection criteria for operational NPPs. The danger of NPP accidents is that even a small defect in critical members of NPPs can result in catastrophic consequences. NDT techniques are now well established and routinely employed for NPP inspection. Despite the merits of NDT techniques, there are, however, several critical limitations. First, NDT often requires a periodic overhaul of the whole NPP facility, reducing its power production efficiency. Furthermore, NDT inspection of NPPs needs to be performed by trained certified engineers, and the inspection typically takes a long time. More importantly, many critical regions cannot be easily accessed by the NDT personnel.

In order to complement NDT techniques, we developed an embeddable fiber guided laser ultrasonic system for NPP inspection, particularly for pipeline systems. The working principle of the proposed embeddable ultrasonic system shown in Figure 12 is basically the same as the previous noncontact laser scanning system. The major difference is that the laser beams in this embedded sensing system are guided through optical fibers. Here, the main concern is to ensure the optical fibers can survive under the harsh operational condition of the NPP facilities such as high radiation and temperature. Special optical fibers were designed and used for high temperature and radiation applications, and validation tests were also conducted by exposing the fibers up to 300 ^{o}C and a typical 5 year Gamma ray radiation of 62.5 kGy. Figure 13 demonstrates that the used optical fibers can survive the high temperature and radioactive environments and still produce a meaningful response compared to the one obtained before exposing the fiber to high temperature and radiation. Subsequent signal processing and damage detection algorithms are also being developed specifically for pipeline structures[31,32].

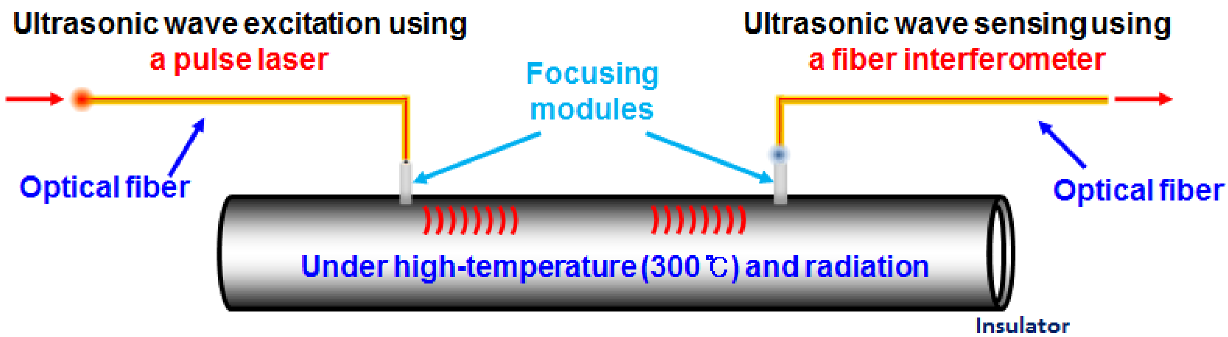


Figure 12. An optical-fiber guided ultrasonic excitation and sensing system for high temperature and radioactive environments

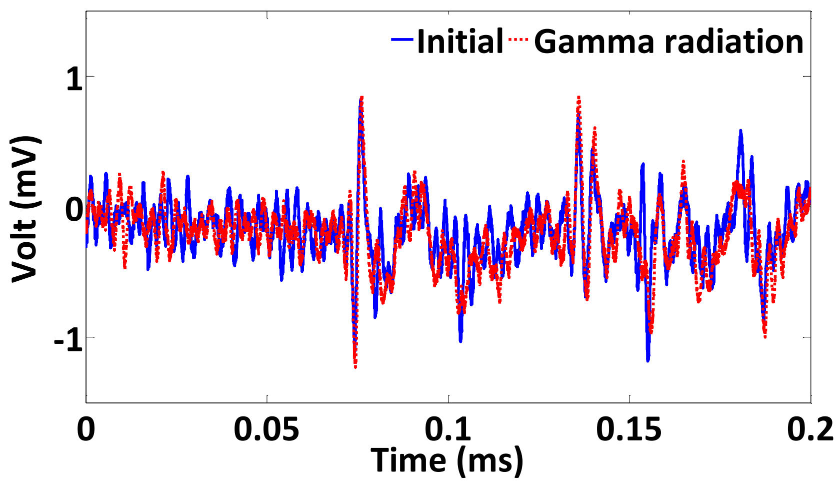


Figure 13. Comparison of ultrasonic signals obtained before (blue solid line) and after (red dotted line) exposing optical fibers to a typical 5 year Gamma ray radiation of 62.5 kGy

4. CONCLUSION

Laser ultrasonics has been around for many years, and it has been extensively studied by the NDT community. Recently, there is an ongoing effort to adopt this technology to SHM applications. It is the author's opinion that noncontact laser ultrasonics particularly will have its own fair share in future SHM applications and can provide the following advantages over conventional sensing techniques: (1) Because noncontact laser ultrasonic scanning techniques can achieve high spatial resolution that most conventional sensing cannot attain, the scanning techniques become sensitive to local small damage. Furthermore, they perform reference-free damage diagnosis without using any previously baseline data obtained from the pristine condition of the system, minimizing false alarms due to changing operational and environmental conditions; (2) Since no sensors or only a few sensors need to be installed for noncontact laser scanning, the laser scanning system can be rapidly deployed, reducing time and costs associated with sensor installation and maintenance. However, it should be noted that there are still many technical hurdles that should be overcome before the noncontact lasers scanning systems can be adopted for SHM applications. For example, data collection using laser scanning takes a long time and requires hardware components more expensive than conventional sensing systems. Furthermore, often special surface treatment is necessary for laser interferometry ultrasonic scanning, and maneuvering of the laser device for large area scanning is another issue that needed to be addressed. Finally, there is a concern for using high-power laser in an open space due to the eye safety issue.

5. ACKNOWLEDGEMENT

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