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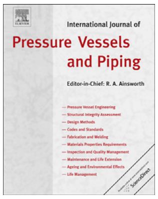

Non-contact imaging of pipe thinning using elastic guided waves generated and detected by lasers

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ABSTRACT

Defect images in a plate can be obtained by the generation and detection of flexural elastic waves using a pulsed laser and a laser Doppler vibrometer. The author has developed an experimental system—called an E-camera—that establishes extremely fast imaging. This paper describes the application of the E-camera to imaging of pipe thinning. The first experiments using a straight pipe revealed that resonance patterns appear significantly at certain frequencies due to guided waves propagating both in the longitudinal and circumferential directions, which is a unique characteristic of pipe structures. A pipe thinning located at various circumferential positions could also be visualized appropriately. Moreover, pipe thinning was successfully detected in both straight and branch pipes located at a distance of 6.0 m from the E-camera system.

1. Introduction

A large number of pipes in industrial plants such as chemical plants and nuclear and thermal power stations are aging, and pipe maintenance is becoming a major burden for plant operators. Although visible pipe surfaces can be inspected easily with human eyes, optical cameras, and/or infrared cameras, invisible inner defects such as pipe thinning due to erosion and corrosion have to be inspected using more laborious techniques such as X-rays and ultrasonic testing [1,2]. In X-ray testing, the transmission intensity of the X-rays, corresponding to the wall thickness of a pipe, is projected onto a film. Although one can inspect pipe thinning such as erosion and corrosion easily using the X-ray image, it requires installation of large equipment and a film located close to the pipe to be inspected. In ultrasonic testing, pipe thickness is measured with an ultrasonic pulse/echo method using a contact transducer. Although ultrasonic testing can be implemented easily without special care and protection devices like X-rays, one can inspect only a small area under the transducer in a single measurement. In other words, these techniques require much greater time and cost than the visual inspection in the process of installation of equipment, preparation, measurement, and evaluation. Moreover, pipes located at great heights require scaffolding to facilitate the inspection, and large-scale work would be necessary even for inspecting small areas.

Therefore, efficient ultrasonic inspection using guided waves propagating in the longitudinal direction in a pipe has attracted much attention [3–6]. Most guided-wave inspection systems employ piezoelectric ultrasonic transducer arrays or magnetostrictive sensors for generating and receiving a torsional mode because the torsional mode is effective for long range inspection owing to its prominent characteristics of no dispersion and small attenuation. However, in the guided wave pipe inspection, one encounters the problem of a trade-off between long-range propagation and defect detectability. Although a low frequency range should be used for long range propagation, guided waves in the high frequency range are necessary for detecting small defects [7,8]. Moreover, guided wave pipe inspection still has an issue regarding the reliable inspection of complex pipe systems like branch pipes and a pipe elbows because guided waves distort significantly at non-straight areas [9].

The author and his colleagues have previously described a new defect-imaging technique using the characteristics of low frequency flexural guided waves and proved that defect images can be obtained with non-contact measurements using plate specimens engraved artificial defects on the back surface [10–15]. Elastic flexural waves were generated by the thermo-elastic effect in response to the laser irradiation of the surface of a plate, and the elastic waves propagating in the plate were detected by a laser Doppler vibrometer (LDV). Because the energy of the elastic wave generated at the laser spot corresponds to the plate thickness at the

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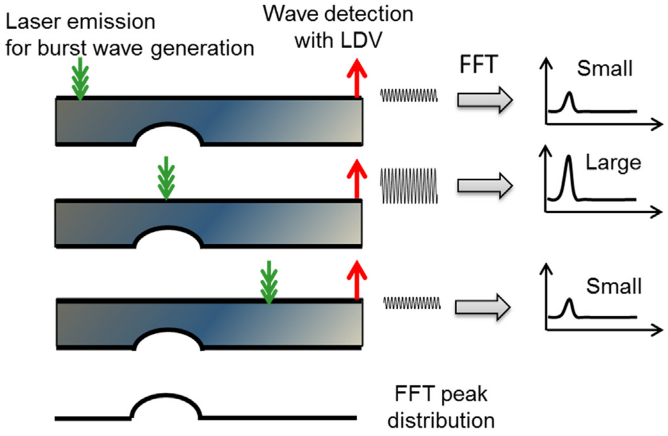

Fig. 1. Principle of defect imaging using the E-camera.

point where the laser beam impinges and the defect depth in the vicinity of the laser source, defect images can be created from the amplitude distributions obtained by scanning the laser source. The author and his colleagues have developed a fast imaging system, in which defect images can be created within a few seconds by non-contact measurements simulating an optical camera.

Fundamental studies on the “Elastic wave camera (E-camera)” have previously been conducted for flat plates. The present study investigates defect imaging using the E-camera system for pipes that are in the greatest demand in plant maintenance.

2. Outline of the E-camera

In the E-camera, an A0 mode of Lamb waves in a low frequency range is generated by a pulsed laser in a plate-like structure and the flexural vibration is detected with the LDV at a surface of the plate. If the thickness at the laser radiation point is small or if defects (reflection sources) are located in the vicinity of the laser radiation point, the energy of the generated flexural waves varies. For example, large signals are detected by the LDV for a plate with a defect on the back surface when the laser pulse for generating elastic waves is incident on the surface opposite to the defect area. On the contrary, when the laser impinges on an intact area, the LDV detects smaller signals as shown in Fig. 1. Using this characteristic of flexural elastic waves, rastering the laser source and mapping the distribution of signal amplitude or frequency spectrum peak detected by a fixed receiving device provide a defect image as shown in the lower sketch of Fig. 1 [10–15]. Because this imaging technique works in the frequency range of audible sound for a plate with the thickness on the order of a few mm, non-contact detection using air-coupled transducers has become feasible [11]. The use of the low frequency range leads to the resonance patterns in the images. Because the resonance patterns differ for different frequencies and receiving positions, the author proved that taking an average of multiple images at different frequencies and positions provides a clearer defect image [11,13,15]. In Ref. [14], non-contact LDV measurements were implemented with high signal-to-noise ratio (SNR) in the frequency domain at a low peak energy with modulated laser pulse trains generated by a high-repetition-rate fibre laser instead of the Nd:YAG laser with giant pulse energy that is generally used for laser ultrasonic generation. In Ref. [15], the effect of high-speed imaging was discussed and it was proved that defect images can be obtained within a few seconds. Moreover, Ref. [13] demonstrated that this imaging technique can provide an image in complex plate-like structures where a direct propagation path does not exist. The results obtained so far imply that irradiating a plate-like structure with pulsed laser beams provides defect images within a few seconds. Because one can create defect images easily with a mode of operation that is similar to an optical camera, we call this measurement system an “E-camera”.

3. Imaging a straight pipe

Fig. 2 shows the E-camera system used in this study. The fibre-laser equipment irradiates the test object with high-repetition-rate laser pulses modulated by external rectangular signals. The modulation frequency of the burst signals was varied from 22 kHz to 36 kHz as shown later, and the time duration of the burst signals was set to 1500 μs. The use of fiber laser equipment and the modulation of the laser pulse emission enable us to generate long-duration burst waves, leading to improve signal to noise ratio in frequency domain [14,15] The elastic wave generated by the fibre laser propagated in the pipe as a guided wave, and was then detected by the LDV (Polytec OFV-5000) at the edge of the pipe. Compared with the experiments of high-speed imaging in Ref. [15], in this study, laser pulse trains were generated at the larger interval of 12.5 ms, and waveforms at 10 ms after the laser emission were used for taking the FFT to maintain a high SNR in the frequency domain. Thus, because the laser source repeatedly moves at 12.5 ms intervals, the required time was approximately 12.5 ms × the number of rastering points. The distances between the E-camera

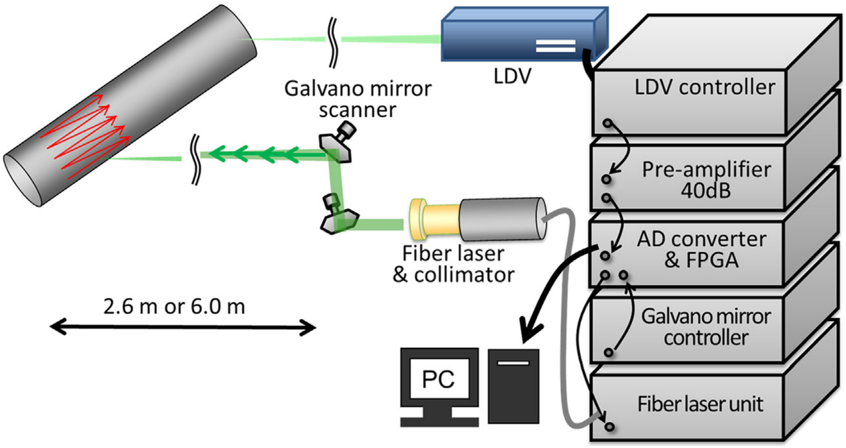

Fig. 2. Schematic figure of the E-camera system.