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Damage detection in pipes based on acoustic excitations using laser-induced plasma

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A health-monitoring system is proposed to detect holes drilled in a pipe based on laser plasma acoustic excitations and acoustic measurements. In this system, an acoustic excitation is applied to a pipe via a laser-induced plasma in air generated by a high-power Nd: YAG pulse laser. Laser-induced plasmas can realize non-contact acoustic impulse excitations. A microphone is used to measure the time response of the acoustic pressure. In this study, we focus on the detection of a hole in the pipe. The reflection of the acoustic wave due to a hole drilled in the pipe induces a change in the time response of the acoustic pressure. Applying a continuous wavelet transform to the measured time response data with/without the hole can locate the position of the hole. This study demonstrates the effectiveness of the present damage detection method based on an acoustic excitation using a laser-induced plasma.

1. Introduction

To prevent accidents due to structural failures, machine conditions must be regularly monitored. Vibration-based health monitoring approaches are actively studied in various damage detection fields such as crack/failure detection in a structure and bolted joint loosening detection. In these studies, vibration/acoustic data are measured by a sensor, which includes an accelerometer and microphone, under excitation with an impulse hammer and a piezoelectric actuator or a speaker. Additionally, fiber optic sensors are commonly used for structural health monitoring in various mechanical systems, including aircraft composite structures [1].

In recent years, health monitoring of infrastructure (e.g., roads, bridges, and pipelines) has received increased attention because effective maintenance of aging infrastructure is imperative to ensure safe and reliable structures. Several approaches have been investigated to detect the loosening of bolted joints. These include using impedance [2,3], electrical conductivity [4], and vibration measurements [5]. Vibration-based approaches commonly involve contact excitations using piezoelectric materials or impulse hammers to excite a structure and determine the frequency response. However, the excitation device must be firmly attached to the structure to use piezoelectric components. Larger sized piezoelectric components may need to be bolted to the structure. Hammering methods require specially trained technicians and are time consuming. Although dynamic characteristic measurements must be highly reproducible to be useful, the reproducibility of the input characteristics with a hammer is poor. These issues have led to research into non-contact excitation methods with a better reproducibility [6].

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Acoustic excitation with a speaker can effectively realize non-contact excitation with a high reproducibility. Several methods have been proposed to generate impulse sound sources, including those employing speakers [7], a spark discharge [8], and a wire explosion [9]. However, these methods require device (e.g., speakers and wires) setup in a sound field, which may disturb the sound field. Moreover, the setup is extremely difficult when the sound field is inside a closed container or filled with materials harmful to humans like carbon dioxide. In research on damage detection in pipes, approaches using ultrasonic guided waves [10–12] and pattern recognition techniques [13] have been investigated. These techniques require that the excitation and measurement devices are attached to the structures.

We have realized an ideal point excitation using a laser excitation method based on laser ablation (LA) [14–20], but the LA-generated excitation induces sub-millimeter-sized damage onto the laser-irradiated surface of a structure. From the viewpoint of non-contact and non-destructive acoustic excitations, several methods using a point sound source generated by a laser-induced plasma (LIP) have been proposed for acoustic tests [21–24]. The LIP is a phenomenon where electrons emitted from atoms and molecules that absorb multiple injected photons produce a plasma via a focused laser beam into a gas.

Many studies have investigated LIPs [25]. For example, ignition with a laser spark [26], LIP spectroscopy [27], and LIP in water [28]. Accurate frequency characteristics have been measured by LIP excitations [29–31]. This approach has been applied to evaluate the firmness of apples [32] and to detect damage in membrane structures [33]. It is expected that combining an LIP acoustic excitation and a health monitoring approach will enhance the efficiency and accuracy of damage detection because excitation devices do not need to be placed in an acoustic field or on the structure.

Herein a damage detection system is demonstrated on the basis of an LIP acoustic excitation and acoustic measurements assuming that a hole drilled on a pipe structure induces damage. This excitation method has the following advantages. First, the excitation force can be applied in a non-contact manner without placing an excitation device such as an exciter or actuator on the target. This is beneficial because placing a device on the target may change the dynamic characteristics of the target structure. In the present technique, an excitation force is provided in a non-contact manner. Second, a high reproducibility can be achieved. The reproducibility of the excitation force in the hammering excitation method depends largely on the skills on the person conducting the measurements. Hence, reproducibility is difficult. On the other hand, a high degree of reproducibility can be assured using a laser excitation method since the excitation force defined by the laser energy is applied.

In the present system, the time history response of the sound pressure is collected by acoustic excitations via an LIP and acoustic measurements by a microphone using an acrylic pipe as the target structure. A continuous wavelet transform is applied to the time variation of the sound pressure inside the pipe, and extracting the reflected waves through the damaged hole identifies the damaged position. Experiments demonstrate that this method effectively and accurately identifies the damaged position.

2. Acoustic excitation via LIP

An LIP refers to a phenomenon where focusing a laser beam onto a gas causes atoms or molecules to absorb many photons by a multiphoton process. Then electrons are emitted and a plasma is formed via a cascade process. The shockwaves formed by converting part of the plasma energy at this time become the sound source via the LIP [29–31].

Previously, the sound pressure when an LIP is generated was measured using a microphone (Fig. 1) to evaluate the acoustic excitation characteristics [29]. For the time history response waveforms of the sound pressure for a point sound source via an LIP, Fig. 2 shows a diagram with an enlarged time axis around the sound pressure generation point. Fig. 3 shows the corresponding Fourier spectrum. Fig. 2(a)–(c) shows the results when the focal length l_f of a lens is 100 mm

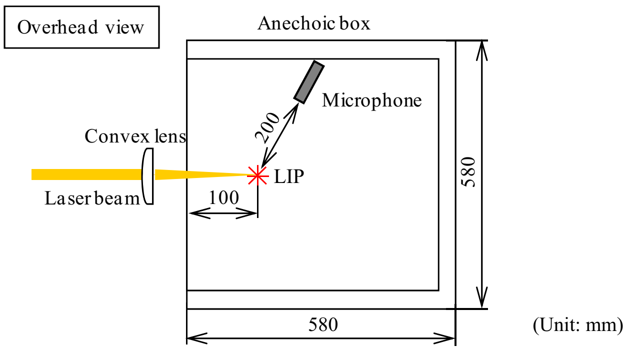

Fig. 1. Acoustic excitation by LIP [29].