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Laser lock-in thermography for detection of surface-breaking fatigue cracks on uncoated steel structures

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ABSTRACT

This paper develops a new noncontact laser lock-in thermography (LLT) technique for detection of surface-breaking fatigue cracks on uncoated steel structures with low surface emissivity. LLT utilizes a modulated continuous (CW) wave laser as a heat source for lock-in thermography instead of commonly used flash and halogen lamps. LLT has the following merits: (1) the laser heat source can be precisely positioned at a long distance from a target structure thank to its directionality and low energy loss, (2) a large target structure can be inspected using a scanning laser heat source, (3) no special surface treatment of the target structure is necessary to generate and measure thermal wavefields, (4) thermal image noises created by arbitrary surrounding heat sources can be effectively eliminated and (5) the use of a low peak power laser makes it possible to avoid surface ablation. The LLT system is developed by integrating and synchronizing a modulated CW laser, a galvanometer and an infrared camera. Then, a fatigue crack evaluation algorithm based on a holder exponent analysis is proposed. The performance of the proposed LLT technique is validated through thermal wavefield imaging and fatigue crack evaluation tests on an uncoated steel plate with emissivity of 0.8 and a welded T-shape joint with emissivity of 0.7. Test results confirm that thermal wavefield images are effectively captured even when surface-reflected background noises and laser-generated thermal waves coexist, and surface-breaking cracks are successfully evaluated without any special surface treatment.

1. Introduction

A fatigue crack is one of the most critical damage types in metallic structures. It has been reported that approximately 90% of failures of in-service metallic structures result from fatigue cracks [1]. Nevertheless, it is often difficult to detect a fatigue crack initiated by repeated loadings below the yield stress of a target structure. To effectively detect such a fatigue crack at its initial stage, a number of nondestructive evaluation (NDE) techniques have been developed. One of the most widely accepted NDE techniques is linear ultrasonic techniques which utilize reflection, refraction, transmission and mode conversion phenomena in ultrasonic propagation to identify a fatigue crack [2–4]. More recently, it has been reported that nonlinear ultrasonic techniques are more sensitive to fatigue cracks than the linear ultrasonic ones [5–7]. However, these ultrasonic techniques often require complex signal processing for crack identification, and crack localization is still a challenging task due to multiple reflections from structural boundaries. In particular, ultrasonic nonlinearities induced by other nonlinear mechanisms such as complex structural features and hardware electronic systems can cause false alarms.

As an alternative to the ultrasonic techniques, active infrared (IR) thermography techniques are gaining popularity because they are noncontact, nonintrusive, rapidly deployable and applicable to structures under harsh environments. Pulse thermography [8–10], lock-in thermography [10–12] and frequency modulated thermography [10,13,14] techniques are among the most widely accepted active IR thermography NDE techniques. These active IR techniques utilize external heat sources such as high-power optical lamps to create thermal wavefields on a target structure, thus making it possible to discern differences in heat flux characteristics between intact and defect areas. However, these IR techniques are mainly applicable to delamination detection in composites rather than surface crack detection in metals, because these light sources create thermal waves propagating primarily in the through-the-thickness direction of a target structure. Note that thermal wave propagation along the surface is necessary for surface crack detection. Moreover, it is difficult to precisely control the intensity and position of an optical lamp due to its divergence and attenuation characteristics.

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As for surface crack detection, eddy-current thermography [15–17] and thermosonic [18–20] techniques have been proposed. A thermosonic technique uses a contact-type transducer to generate an ultrasonic input, and the local heating created by the ultrasonic excitation at a crack interface is captured by an IR camera. In an eddy-current technique, eddy current is produced on a target surface using a coil carrying current in proximity based on electromagnetic induction, and the disturbance of the eddy-current and subsequently local heating due to surface crack formation is detected by an IR camera. Here, the thermosonic technique requires a contact transducer, and the working distance from the eddy current probe to the specimens is limited below several cm.

More recently, laser thermography has been proposed for crack detection. The use of a laser beam as a heat source allows (1) transmitting heat energy over a long distance, (2) precisely controlling the intensity and position of the laser beam, and (3) creating thermal wave propagation along a target surface, making it possible to detect surface cracks. Li et al. utilized a high-power pulse laser of 21 W as a heat source for surface-breaking crack detection in a metallic structure [21]. Then, Schlichting et al. successfully detected a surface crack using a high-power continuous wave (CW) laser of 5.2 W [22]. However, the exposure of the target structure to repeated high-power laser beams can result in surface ablation [23]. Furthermore, their applicability to metallic structures with low emissivity is often limited even with high-power laser, and the thermal images captured by an IR camera can be disturbed by reflections of arbitrary surrounding heat sources on a target surface with low emissivity. Therefore, often special surface treatments of target specimens are necessary. Note that the previous laser thermography studies utilized the specimens with black surface coating to achieve high emissivity (>0.95) [22].

In this study, a new laser lock-in thermography (LLT) technique is developed so that incipient fatigue cracks in uncoated metallic structures can be detected using low peak power laser even when a structure with low emissivity is exposed to other surrounding heat disturbances. First, a new LLT system is developed by synchronizing (1) a modulated CW laser beam used as a hear source, (2) a galvanometer for spatial scanning of the laser beam and (3) an IR camera for thermal wavefield measurement. Second, a discontinuity detection algorithm based on a holder exponent analysis is proposed for fatigue crack evaluation. Two-step laser scanning is performed for crack identification, localization and quantification. First, sparse laser scanning is conducted to identify and localize a fatigue crack, and then dense laser scanning is performed only for nearby the identified crack location for crack length quantification. The performance of the proposed LLT technique is experimentally examined through thermal wavefield imaging and fatigue crack evaluation on an uncoated steel plate with emissivity of 0.8 and a welded T-shape joint with emissivity of 0.7.

This paper is organized as follows. First, the development of the proposed LLT hardware system is described in Section 2. Then, the fatigue crack detection algorithm based on the holder exponent analysis is developed along with a two-step laser scanning strategy in Section 3. In Section 4, real fatigue cracks in a steel plate and a welded joint are identified, localized and quantified using the proposed LLT system. This paper concludes with brief discussions in Section 5.

2. Development of laser lock-in thermography system

The LLT system is composed of excitation laser, IR camera and control units as shown in Fig. 1. The excitation laser unit includes an arbitrary waveform generator (AWG), a laser diode driver (LDD), a CW laser, a collimator and a galvanometer. The CW laser used in this study has a wavelength of 808 nm and a maximum peak power of 40 W. The galvanometer has a maximum rotating

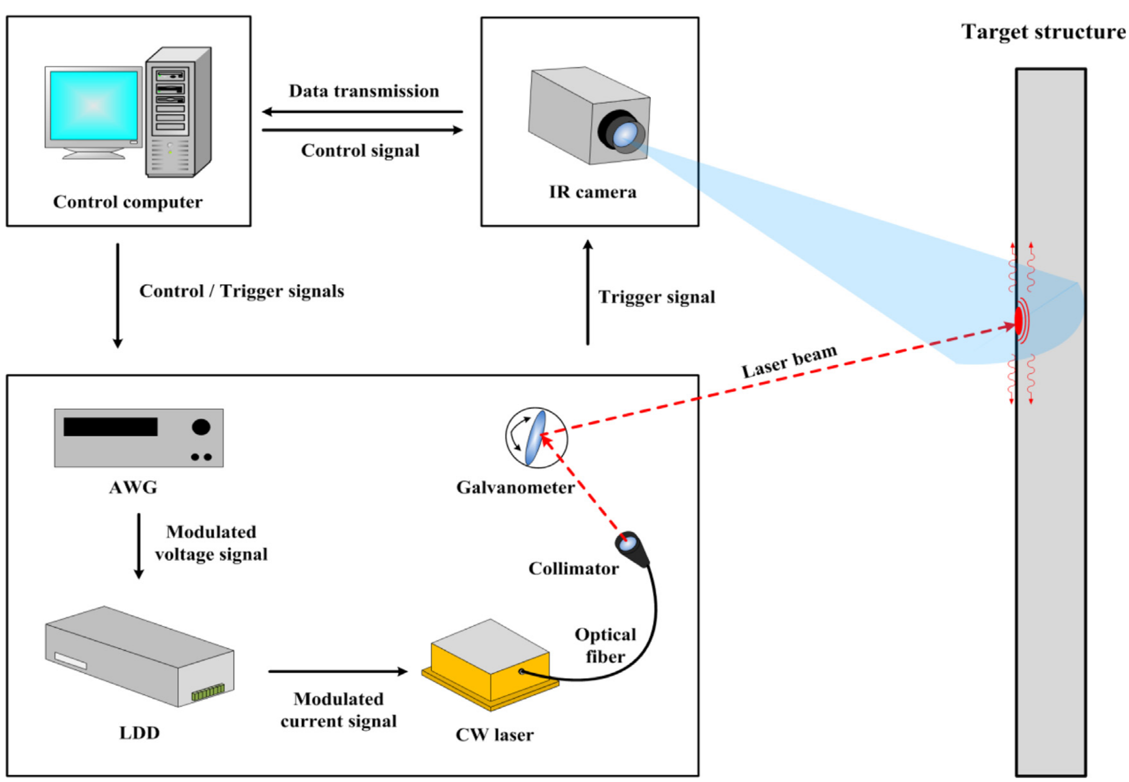

Fig. 1. Schematic diagram of the proposed LLT system: The LLT system is composed of excitation laser, IR camera and control units. The control unit sends out control and trigger signals to the excitation laser unit. Subsequently, the laser beam generates thermal waves at a desired excitation point, and corresponding thermal responses are measured by the IR camera triggered by the control unit. Then, the measured thermal responses are transmitted to and stored in the control unit.