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

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\textbf{A B S T R A C T}

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 wave 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.

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\end{itemize}

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 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.
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 heat 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.
speed of 5730/s, an angular resolution of \(6.6 \times 10^{-4}\), and an allowable scan angle of \(\pm 21.8^\circ\). The IR camera has a temperature resolution of 0.03 K, \(640 \times 480\) pixel, a maximum sampling rate of 60 Hz and wavelengths between 7.5 \(\mu\)m and 14 \(\mu\)m. The control unit consists of a personal computer including data acquisition and processing software.

The working principle of the LLT system is as follows. First, virtual grid points on a target surface are created and the sequence of excitation scanning points is predetermined. Then, the control unit sends a trigger signal to the excitation laser unit to activate AWG. Here, AWG generates a periodic square waveform with a DC offset. The desired voltage signal generated by AWG is amplified and converted into a current signal in LDD. Then, the intensity of the CW laser beam is modulated by the converted current signal, and the laser beam is emitted through an optical fiber and the collimator. Using the galvanometer, the laser beam generates thermal waves at the first prescribed excitation point. The same trigger signal generated by the control unit is also transmitted to the IR camera to synchronize data acquisition with the laser excitation. Then, thermal images are captured by the IR camera, transmitted to and stored in the control unit. Next, the control unit moves the excitation laser beam to the next scanning point by sending another control signal to the galvanometer. By scanning the laser excitation beam over all the prescribed grid points, the corresponding thermal images over the entire inspection area are obtained.

3. Development of a crack evaluation algorithm

In this section, a new crack evaluation algorithm based on a holder exponent analysis is developed to identify, locate and quantify a crack from the thermal wavefield images obtained by the LLT system. The holder exponent analysis was first introduced by Mallat et al. to detect signal singularities based on a wavelet transform [24]. In a similar manner, the presence of a discontinuity in dynamic signals was identified in the time domain [25,26]. More recently, Mani et al. used the holder exponent analysis to measure the local irregularity of images [27]. In this study, the holder exponent analysis is used to detect spatial discontinuities of the thermal flux created by a surface crack from the measured thermal images. The algorithm is composed of four steps as outlined in Fig. 2, and the details of each step are described below.

3.1. Compute a lock-in amplitude image for a specific laser excitation point

Once thermal images are collected in the time domain using the LLT system, a lock-in amplitude image at a specific time is computed from the thermal images. When the excitation laser beam modulated by a periodic square waveform is illuminated onto a target surface, the target surface undergoes repeated heating and cooling as shown in Fig. 3. Once a thermal response, \(R(x,y,t)\), is captured by the IR camera, a lock-in amplitude value at a specific spatial \((x,y)\) and time \(t\) point is defined as:

\[
A(x,y,t) = \sqrt{\left(R(x,y,0) - R(x,y,t/2)\right)^2 + \left(R(x,y,t/2) - R(x,y,t)\right)^2}
\]

where \(0 < t \leq T\). \(T\) denotes a period of the input signal.

Subsequently, a single lock-in amplitude image can be constructed by assembling the lock-in amplitude values from all spatial points of interest as shown in the step (1) of Fig. 2. Note that, because only the thermal gradients locked in with the heating and cooling processes...
appear in the lock-in amplitude image, the thermal disturbances caused by the other heat sources, which are not synchronized with the excitation laser beam, disappear from the lock-in amplitude image.

3.2. Compute a discontinuity image for the kth laser excitation point

Once the lock-in amplitude image is constructed, a discontinuity image is computed by applying the holder exponent analysis to each row and column of the lock-in amplitude image. First, all the pixel values in the discontinuity image, $X^k$, corresponding to the kth laser excitation point are initialized to be zeros.

Second, the wavelet transform of the first row of the lock-in amplitude image, $f(x)$, is taken, and the absolute value of the resulting coefficient is obtained as follows [25]

$$|Wf(x,s)| = \left[ \int_{-\infty}^{\infty} f(u) \frac{1}{\sqrt{s}} e^{iu \psi(s)} du \right]$$

(2)

where $Wf(x,s)$ is the wavelet transform coefficient at spatial translation $x$ and scale $s$, $u$ is a spatial point, and $*$ denotes the complex conjugate. Haar wavelet is used as the basis function.

Third, the wavelet transform coefficients computed from Eq. (2) are arranged in a two-dimensional matrix format. Each row and column of the matrix represents different spatial point ($x$) and frequency scale ($s$), respectively. From the matrix, the holder exponent value at a specific spatial point $x$ is obtained by simply computing the slope of the wavelet coefficient values along $s$-axis [25].

Then, the maximum holder exponent value is taken and registered to the corresponding pixel point in the discontinuity image, $X^k$. Note that the holder exponent value is expected to increase at spatial discontinuities. That is, crack formation produces a sudden discontinuity within the lock-in amplitude image, and the contribution of higher frequency wavelet coefficients near the crack location increases. This rising contribution of the higher frequency values, in return, increases the holder exponent value. The calculation of the maximum holder exponent value is repeated for all rows in the lock-in amplitude image, completing the row-wise discontinuity image, $X^k$.

Fourth, the previous procedures are repeated column-wise instead of row-wise, producing another discontinuity image $Y^k$. Then, the final discontinuity image for the kth laser excitation point is defined as follows:

$$Z^k_{ij} = \sqrt{(X^k_{ij})^2 + (Y^k_{ij})^2}$$

(3)

where $X^k_{ij}$ and $Y^k_{ij}$ denote the $ij$th entity of the row-wise and column-wise discontinuity images, respectively.

3.3. Construct the final discontinuity image by superimposing the discontinuity images from all excitation points

So far the steps (1) and (2) are performed for a specific laser excitation point. By repeating the previous steps for all laser excitation points of interest, the final discontinuity image can be obtained as follows:

$$S^k_{ij} = \sum_{k=1}^{n} Z^k_{ij}$$

(4)

where $S^k_{ij}$ is the $ij$th entity of the final discontinuity image, $n$ denotes the number of laser excitation point.

3.4. Visualize the crack after denoising the final discontinuity image

Since the final discontinuity image obtained in the step (3) still contains undesired noise components as shown in Fig. 2, only the pixel values exceeding a certain threshold value is visualized. The threshold value is determined by employing an extreme value statistics [28]. First, the probability density function of the pixel values in the final discontinuity image is estimated by fitting a type III extreme value distribution also known as a Weibull distribution to all the pixel values. Then, the threshold value corresponding to a one-sided 97% confidence interval is calculated. Finally, only the pixel values above the computed threshold value are retained in the final image, making it possible to visualize only crack formation as shown in the step (4) of Fig. 2.

For precise crack estimation, a two-step laser scanning strategy is proposed as shown in Fig. 4. First, a crack is identified and
Fig. 5. Experimental setup for a cyclic loading test: (a) A specimen under a universal testing machine (UTM) and (b) a dog-bone shape steel specimen.

Fig. 6. The crack widths estimated from microscopic images: (a) 54.702 μm at the notch tip and (b) 38.667 μm at the crack tip.

Fig. 7. Laser lock-in thermography setup for thermal wavefield imaging.
localized through sparse laser scanning, and then the crack length is quantified by dense laser scanning near the crack location identified by the previous sparse laser scanning. Each scanning scheme shares an identical image processing algorithm based on the holder exponent analysis.

4. Experimental validation

4.1. Creation of a fatigue crack

To examine the performance of the proposed LLT technique, a fatigue crack evaluation test is performed. First, a fatigue crack is created in a dog-bone shape SS400 steel plate using a universal testing machine (UTM) as shown in Fig. 5(a). The emissivity of the steel specimen is experimentally estimated to be 0.8 using a black-body radiator. Then, a 10 mm-long and 1 mm-wide initial notch is introduced to induce stress concentration under cyclic loading as shown in Fig. 5(b). The cyclic loading ranges from 2.8 to 28 kN with a loading cycle of 10 Hz. After 10,000 cycles, a fatigue crack is initiated from the notch tip. Fig. 6 shows the fatigue crack widths estimated from microscopic images near the notch and crack tips after 26,000 loading cycles. The crack width is approximately 54.702 μm at the vicinity of the notch tip and 38.667 μm at the crack tip. The crack length is estimated to 9.5 mm.
4.2. Laser lock-in amplitude imaging

The effectiveness of the proposed LLT technique for a laser-generated thermal wavefield imaging is experimentally examined. The experimental setup is shown in Fig. 7. A periodic square signal with a frequency of 0.1 Hz is generated using AWG. This voltage signal is amplified and converted into the current signal in LDD, which subsequently modulates the intensity of the CW laser beam. The modulated CW laser beam is transmitted through the optical fiber, the collimator and the galvanometer for laser scanning. The laser peak power of only 3.8 W is used in the test although the maximum allowable peak power is 40 W and the emitted beam size through the galvanometer is about 15 mm. The distance between the galvanometer and the specimen is 600 mm, and the IR camera is 400 mm apart from the specimen. The sampling rate of the IR camera is 50 Hz.

Fig. 8 shows an example of laser excitation within an intact area of the specimen. The representative snapshots of the corresponding raw thermal images at 0.1 s, 0.5 s, 1 s, 2.5 s and 10 s are shown in Fig. 9(a). Here, $T=10$ s. The heat emitted from the IR camera itself is reflected from the specimen and captured by the IR camera, creating the rectangular thermal pattern throughout the whole specimen.

Fig. 11. Sparse and dense laser scanning schemes for fatigue crack evaluation: Point A denotes a dense laser scanning point.

Fig. 12. (Color online) Representative thermal images produced by a single point laser excitation at Point A shown in Fig. 11: (a) Raw thermal images and (b) lock-in amplitude images at 0.1 s and 10 s. Heats reflected from the IR camera appear in the raw thermal image, while only laser-generated thermal wavefields are visible in the lock-in amplitude images.
snapshots. Overwhelmed by this IR camera heat, laser-generated thermal wavefields cannot be properly observed. On the other hand, the IR camera heat pattern is removed in the corresponding lock-in amplitude images, and only the laser-generated thermal wavefields are clearly shown in Fig. 9(b). Moreover, Fig. 9(b) shows that the lock-in amplitude images effectively visualize thermal wave propagation outward from the excitation point as time elapses, making it possible to significantly enhance the crack detectability in the subsequent fatigue crack evaluation.

To further investigate the difference between the raw and lock-in images, the thermal profile across the illuminated laser spots are compared in Fig. 10. Because the incident laser beam intensity has a Gaussian distribution, the thermal profiles across the laser spots follow Gaussian distributions as well. Note that the thermal profiles in Fig. 10 are normalized using their maximum values.

Table 1

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated crack length (mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microscopic imaging</td>
<td>9.5</td>
<td>Reference value</td>
</tr>
<tr>
<td>Sparse laser scanning</td>
<td>8.2</td>
<td>13.7</td>
</tr>
<tr>
<td>Dense laser scanning</td>
<td>9.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The raw thermal profiles at 0.1rm and 10rm have different mean values ($\mu_1 \neq \mu_2$) as shown in Fig. 10(a), while the lock-in amplitude profiles at the corresponding states have identical mean values ($\mu_1 = \mu_2$) as displayed in Fig. 10(b). The mean difference in the raw thermal profiles is caused by the heating reflected from the IR camera, making it difficult to properly visualize the thermal propagation. On the other hand, Fig. 10(b) shows that this heat disturbance is eliminated in the lock-in amplitude profiles.

4.3. Fatigue crack evaluation in a steel plate

Now, the performance of the proposed LLT technique for fatigue crack evaluation is examined using thermal data obtained from the uncoated steel plate prescribed in Section 4.2. Fig. 11 shows the laser scanning schemes used in the test. The laser beam with a diameter of 15 mm is scanned over the fatigue crack with a spatial resolution of 30 mm for sparse laser scanning. Once the crack location is identified through sparse laser scanning, a dense laser scanning point is subsequently determined. Here, a single laser point (A) is enough to cover the whole fatigue crack length as shown in Fig. 11, although multiple dense laser scanning points might be necessary.

The representative thermal images obtained from Point A are displayed in Fig. 12. Laser-generated thermal wavefields and

![Fig. 13](image-url). Fatigue crack length estimation via (a) sparse laser scanning and (b) dense laser scanning.

![Fig. 14](image-url). Description of a T-shape steel specimen: (a) Overview and side view and (b) laser scanning scheme. Points B and C are laser excitation points near intact and crack areas, respectively.
thermal images reflected from the IR camera coexist in the raw thermal images in Fig. 12(a), thus making it difficult to precisely evaluate the fatigue crack. On the other hand, lock-in amplitude images eliminate the influence of the IR camera heating and show only laser-generated thermal wavefields, enabling to clearly observe thermal wave blocking by the fatigue crack formation as shown in Fig. 12(b).

In Table 1 and Fig. 13, the fatigue crack lengths assessed by three different methods are compared. The fatigue crack length is estimated to be 9.5 mm through microscopic imaging of the specimen as shown in Fig. 6, and this value is considered the reference value in this experiment. From sparse scanning in Fig. 13(a), the existence and location of the crack is clearly identified without any prior knowledge of the fatigue crack, but the crack length is underestimated to be 8.2 mm. Fig. 13(b) which is the resultant image by applying the holder exponent analysis to Fig. 12(b) at 10 s through Eqs. (2) and (3), reveals that the crack length estimated through dense laser scanning is 9.4 mm and only 1.1% different from the reference value.

4.4. Crack evaluation in a welded joint of a T-shape steel structure

The capability of the proposed LLT technique to detect a crack at a welded joint of a T-shape steel structure is also investigated. The target specimen is fabricated by welding a vertical stiffener to a SS400 steel plate as shown in Fig. 14(a). Note that the surface emissivity of the specimen is experimentally measured to be around 0.7. Using precision laser cutting, a crack with a dimension of $10 \times 0.25 \times 0.99 \text{ Nm}^3$ is introduced at a heat affected zone, where stress concentration is expected to occur [29]. The laser

Fig. 15. Representative thermal images obtained from Points B and C at 10 s: (a) Raw thermal images and (b) lock-in amplitude images. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 16. Crack estimation at the intact and crack regions: No indication of crack when the laser beam is exerted on the intact area (Point B), while crack is visualized when the laser beam is illuminated onto the crack area (Point C).
beam is exerted on Points B and C representing intact and crack areas, respectively, so that thermal images from these two regions can be compared. Note that a single laser point excitation (C) is enough to cover the entire crack length as shown in Fig. 14(b). The rest of the test setup is identical to the one in Section 4.2.

The representative thermal images obtained when the laser beam is exerted at Points B and C are shown in Fig. 15. The thermal images of the laser beam reflected from the steel plate appear on the vertical stiffer as shown in Fig. 15(a). Furthermore, the thermal waves are blocked by the welding zone, making it difficult to identify the crack. On the other hand, the thermal wave blocking due to the crack is better observed from the lock-in amplitude image shown in Fig. 15(b), although it is less obvious than the previous example in Fig. 12(b). This degraded performance in Fig. 15(b) is attributed to the fact that the present crack is only 0.99mm deep out of the 5mm thick specimen, while a through-the-thickness crack is investigated in Fig. 12(b).

Once the proposed algorithm is applied to the lock-in amplitude images obtained from Points B and C, crack estimation is performed as shown in Fig. 16. Fig. 16(a) shows no indication of crack when the laser beam is exerted on Point B, while crack is visualized when the laser beam is illuminated at Point C as shown in Fig. 16(b). The crack length is estimated to be 10.75mm, which is 7.5% longer than the actual crack length.

5. Conclusion

This paper presents a new laser lock-in thermography (LLT) technique for surface-breaking fatigue crack estimation for uncoated steel structures. The LLT technique offers improved thermal wavefield imaging by eliminating the effects of unwanted surrounding heat sources and enhances the detectability of an incipient fatigue crack. A LLT hardware system is developed using a modulated continuous wave laser with a galvanometer and an infrared camera. Then, an accompanying crack evaluation algorithm using a holder exponent analysis and an extreme value statistics is proposed for crack identification, localization and quantification. The test results show that the LLT technique successfully detects a fatigue crack with a width below 50μm.

Before the proposed LLT technique can make a transition to field applications, there are still technical hurdles need to be overcome. First, the surface irregularity of a target structure can significantly affect the performance of the proposed LLT technique. Indeed, the elimination of the surface irregularity effect without using baseline data is a challenging task. Second, the current inspection time for large structures can be prohibitively long using point source scanning. This inspection time can be significantly reduced using a line scanning source for time pressing applications, which is now being investigated. Finally, the applicability of the LLT technique to structures with extremely low emissivity might be limited because the heat absorption from the laser beam might not be sufficient to generate thermal waves. Further studies are warranted to address these issues.

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Reference