Noncontact fatigue crack visualization using nonlinear ultrasonic modulation

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ABSTRACT

This paper presents a complete noncontact fatigue crack visualization technique based on nonlinear ultrasonic wave modulation and investigates the main source of nonlinear modulation generation. Two distinctive frequency input signals are created by two air-coupled transducers and the corresponding ultrasonic responses are scanned using a 3D laser Doppler vibrometer. The effectiveness of the proposed technique is tested using aluminum plates with different stages of fatigue crack formation such as micro and macro-cracks. Furthermore, the main source of nonlinear modulation is discussed based on the visualization results and the microscopic images.

1. Introduction

90% of failures of in-service metallic structures are attributed to fatigue cracks [1]. All metallic structures initially exhibit material nonlinearity such as dislocation and initial micro-crack/voids over the entire volume. Under repetitive loading, the stress is concentrated at damage precursors and later dissipated by plastic deformation. With more cycles of loading, micro-cracks are nucleated at the grain boundaries and coalesce and grow into a macroscopic crack. Then, the macro-crack starts to propagate. At this point, micro-cracks and a plastic zone, where stresses are highly localized, and are formed ahead of the crack tip as shown in Fig. 1 [2]. As the macro-crack continues to propagate, the plastic zone leaves a trace called “plastic wake” along the crack surface and a new plastic zone is formed at the crack tip.

A fatigue crack often becomes conspicuous only after the crack reaches about 80% of the total fatigue life for most metallic materials [3]. For example, the worst high-speed train derailment in history, the Eschede train disaster in Germany in 1998, resulted from a hidden single fatigue crack in one of the train wheels [4]. Nonlinear ultrasonic techniques, which look for nonlinear characteristics such as harmonics and modulations (spectral sidebands) generated by damages, have emerged as promising tools for fatigue crack detection. It is known that the sensitivity of the nonlinear ultrasonic techniques to damages is far better than that of the linear ones [5,6].

The nonlinear modulation technique, which utilizes spectral sideband components for damage detection, is one of available nonlinear ultrasonic techniques [7,8]. When two sinusoidal waves at distinctive frequencies propagate through a media with a nonlinear source such as a fatigue crack, these two propagating waves interact with each other and produce spectral sidebands at the sum and difference of the two frequencies.

The nonlinear modulation technique was used to detect cracks in welded pipe joints inside a nuclear power plant and cracks in concrete beams [9,10]. A fatigue crack in an aluminum plate was detected using a piezoelectric (PZT) stack actuator for generation of a low frequency (LF) input and a surface-mounted PZT for creation of a high frequency (HF) input [11]. The usage of two surface mounted PZTs for generation of both LF and HF high-voltage inputs was investigated to detect bolt-loosening in an aluminum lap joint and delamination in composites [12,13]. Yoder and Adams fixed the frequency of the LF input and swept the HF input to find an optimal combination of the HF and LF frequencies that can amplify the modulation level [14]. Actual fatigue cracks in a mock-up aircraft fitting-lug with complex geometries were detected by constructing the first sideband spectrogram by sweeping both input frequencies [15]. Recently, a reference-free fatigue crack detection technique, which does not rely on baseline signals obtained from the intact condition of a target structure, was also developed based on nonlinear ultrasonic modulation [16].

A laser based noncontact fatigue crack detection technique was developed by Liu et al [17]. A broadband ultrasonic wave was generated by a Nd:Yag pulsed laser and the corresponding response was measured by a single laser Doppler vibrometer (LDV). A fatigue crack is detected by counting the spectral peaks produced by modulation among the broadband ultrasonic waves excited by the pulsed laser. Ballad et al. developed a noncontact...
damage visualization technique for simulated defects in a thin plate [18]. Two focused air-coupled transducers (ACTs) with scanning equipment were used for high frequency ultrasonic excitation and sensing. For low frequency excitation, a mechanical shaker or even a loud speaker was used. A harmonic based fatigue crack visualization technique was reported by Kwasim et al. [19]. A micro-crack and plastic deformation at the fatigue crack tip in a stainless steel specimen installed in the water bath was visualized by transmitting 35 MHz sine burst waves and receiving the 3rd harmonic component.

In this study, a complete noncontact fatigue crack visualization technique based on nonlinear ultrasonic wave modulation is developed and its effectiveness in detecting different stages of fatigue cracks is investigated. Ultrasonic waves at two distinctive frequencies are generated by two ACTs, and the corresponding ultrasonic responses are scanned over a target specimen by a 3D LDV, which has high spatial resolution and velocity sensitivity. Then, the spectral sideband components are extracted from the measured responses and visualized over the scanned area. The uniqueness of this study lies in (1) development of a complete noncontact nonlinear modulation technique for fatigue crack visualization, (2) the effectiveness of the proposed technique is tested using aluminum plates with different stages of fatigue crack formation and, (3) the main source of nonlinear modulation is discussed.

This paper is organized as follows. In Section 2, the binding conditions (BCs) for nonlinear modulation and nonlinear modulation generation sources are briefly reviewed. Section 3 describes the development of the proposed noncontact fatigue crack visualization technique. Then, experimental results are reported in Section 4, and the conclusion and discussions are provided in Section 5.

2. Theoretical backgrounds

2.1. Nonlinear ultrasonic modulation

When two waves $a$ and $b$ at the frequencies of $\omega_a$ and $\omega_b$ ($\omega_a < \omega_b$) propagate through a localized crack located at $x = 0$ in a stress-free plate with a thickness of $2h$ ($-h \leq z \leq h$) in the $x$-direction, the solution for the total particle displacement after passing the crack, $u(x)$, can be approximated as the summation of the linear response, $u^{(1)}$, harmonics, $u^{(2)}$, and modulations $u^{(3)}$ due to the interaction between waves $a$ and $b$

$$u(x) = u^{(1)} + u^{(2)} + u^{(3)}$$  \hspace{1cm} (1)

where

$$u^{(1)} = u_a e^{i\omega_a x - \omega_a t} + u_b e^{i\omega_b x - \omega_b t} + c.c.,$$  \hspace{1cm} (2)

$$u^{(2)} = u_{2a} e^{i(2\omega_a x - \omega_b t)} + u_{2b} e^{i(2\omega_b x - \omega_a t)} + c.c.$$

and

$$u^{(3)} = u_a e^{i(\omega_a x - \omega_b t)} + u_b e^{i(\omega_b x - \omega_a t)} + c.c.$$  \hspace{1cm} (4)

where $c.c.$ stands for complex conjugate, $u_a$ and $u_{2a}$ are the amplitudes of the linear component at $\omega_a$ and the nonlinear harmonics at $2\omega_a$, respectively, $u_b$ and $u_{2b}$ are defined similarly. $u_{2a} \pm a = u_{1a} + u_{-a}$ is the amplitude of the first spectral sideband (modulation) at $\omega_b \pm a$ due to the mutual interaction of the linear components. $\omega_a$ and $\omega_b$ are the wavenumbers corresponding to waves $a$ and $b$. For simplicity, the higher order harmonic and modulation components are omitted from the nonlinear solution. In this study, only $u^{(3)}$ is extracted and used for damage detection and visualization.

2.2. Sources of nonlinear ultrasonic modulation

In metallic structures, it has been shown that nonlinear ultrasonic modulation may result from a number of sources summarized as follows [20]:

2.2.1. Material’s intrinsic nonlinearity

A crystallographic defect, or irregularity, within a crystal structure such as dislocation or interatomic potential can be a source of nonlinearity. This nonlinearity is weak and not localized (global characteristic) [21]. However, in some cases, this nonlinearity can give non-negligible contribution to the observed nonlinear-modulation components for localized damage detection.

2.2.2. Initial micro-cracks/voids

The initial micro-cracks/voids in material also cause nonlinearity. In most cases, these initial micro-cracks/voids act as precursors of macro-cracks when the structure is under repeated loading. This nonlinearity is also weak and not localized (global characteristic) [22].

2.2.3. Local plasticity

Local plastic deformation from impact, overloading or stress concentration can generate nonlinearity as the material property becomes locally nonlinear. This nonlinearity is strong and localized [19,23].

2.2.4. Crack opening/closing (contact)

When ultrasonic waves or vibrations are applied, the crack surface can be alternating between open and closed (contact) conditions. This is called ‘breathing crack’ or ‘contact acoustic nonlinearity’ (CAN) [24,25]. The nonlinearity due to the crack opening/closing has strong and localized characteristic than the distributed material intrinsic nonlinearity [26,27]. The contacts between rough crack interfaces can also occur locally while the crack is not completely open and closed, that is called ‘micro-contact’ [28]. Zaitsev et al. hypothesized that the structural nonlinearity is mainly due to the micro-contacts produced by inputs and discussed the validation of the hypothesis [29,30].

2.3. Binding conditions (BCs) for nonlinear ultrasonic modulation

For nonlinear modulation based fatigue crack detection, the frequency combination of LF and HF inputs should be chosen carefully. The BCs for nonlinear modulation for localized nonlinearity such as fatigue crack have been theoretically and

Fig. 1. Mechanism of fatigue crack formation and growth. At the crack tip, a local plastic zone and micro-cracks are formed due to stress concentration.
experimentally investigated by several researchers and the findings can be summarized as follows:

2.3.1. Crack perturbation condition

The wave (or vibration) applied to the structure should perturb the crack opening/closing [31]. For example, in vibration, if the crack is located in a node of the applied vibration mode, the nonlinear component is not generated because the crack does not interact to the applied vibration. Furthermore, the mode type (in-plane or out-of-plane) of input signal also should be carefully determined considering the orientations of cracks so that perturbation the crack opening/closing efficiently.

2.3.2. Nonlinear resonance condition

Especially for vibration, when the modulation frequency coincides with one of the resonance frequencies of the structure, the amplitude of the modulated component is further amplified [14]. Thus, the sensitivity of crack detection can be improved through the amplified nonlinear component due to the nonlinear resonance condition.

3. Development of a noncontact fatigue crack visualization technique

3.1. Hardware configuration

Fig. 2 shows the hardware configuration of the proposed noncontact fatigue crack visualization system. An NI PXI system composed of two arbitrary waveform generators (AWGs, NI PXI-5421) was used for generating sinusoidal input waveforms. For noncontact generation of LF and HF input signals, two ACTs were used.

LDV has been widely used for vibration measurement, and more recently for ultrasonic applications. With scanning capability, LDV can visualize propagating ultrasonic waves and achieve high spatial resolution to localize defects with high velocity sensitivity [32]. When a laser beam is reflected from a vibrating target surface, the frequency of the returned laser beam is shifted. A single LDV measures this frequency shift and relates it to the out-of-plane velocity of the target surface based on the Doppler Effect. For the measurement of in-plane motions, 3D LDV, which is composed of three aligned laser beams, can be used to measure not only out-of-plane but also in-plane motions [33]. In this study, the first sideband components in out-of-plane and in-plane directions are individually visualized using a commercial 3D LDV (Polytect PSV400) to investigate their relative sensitivity to fatigue cracks. The 3D LDV used in this study employs He–Ne continuous wave (CW) laser source of 633 nm wavelength. The NI PXI system and the 3D LDV were synchronized by a pulse triggering signal from AWG 2 to the 3D LDV as shown in Fig. 2.

![Fig. 2. Hardware configuration for non-contact fatigue crack visualization using ACTs for ultrasonic generation and LDV for ultrasonic response scanning.](image)

3.2. Fatigue crack visualization with spatial scanning

Once ultrasonic responses are collected over the entire scan area, fatigue cracks are visualized according to the following steps:

**Step I:** Both LF and HF inputs are applied simultaneously to the structure, and the corresponding ultrasonic response is measured from a single measurement point. Then, the following damage index (DI) is computed at the measurement point \((x, y)\).

\[
\text{DI}(x, y) = \frac{u_{a-b}(x, y) + u_{a+b}(x, y)}{u_a(x, y)}
\]

where \(u_{a-b}(x, y), u_{a+b}(x, y)\) are the amplitudes of the first sideband components at \(\omega_b - \omega_a\) and \(\omega_b + \omega_a\) of the response spectrum, respectively. The amplitude of the first sideband components depends on the amplitude of LF and HF inputs. Thus, the first sideband components are normalized with respect to the multiplication of amplitudes of LF and HF inputs, \(u_a(x, y)\) and \(u_b(x, y)\), respectively.

**Step II:** Second, only HF input is applied, and another ultrasonic response is measured from the same measurement point. Then, the following noise index (NI) similar to DI is computed at the same measurement point \((x, y)\).

\[
\text{NI}(x, y) = \frac{n_{a-b}(x, y) + n_{a+b}(x, y)}{u_a(x, y)}
\]

where \(n_{a-b}(x, y)\) and \(n_{a+b}(x, y)\) are the amplitudes of the noise spectrum at \(\omega_b - \omega_a\) and \(\omega_b + \omega_a\), respectively. Note that, because nonlinear modulation occurs only due to the interaction of HF and LF inputs, \(n_{a-b}(x, y)\) and \(n_{a+b}(x, y)\) are the sole outcome of measurement noises. Here, similar with DI calculation, the first sideband components are normalized with respect to the multiplication of amplitudes of HF and LF inputs.

**Step III:** Steps I and II are repeated for the entire target surface by scanning 3D LDV.

**Step IV:** A threshold value for denoising is established by characterizing the statistical distribution of the NI obtained from the entire scanned surface. The upper tail distribution of the NI values are characterized using a Generalized Extreme Value (GEV) distribution, and a cumulative density function of the GEV distribution, \(F_{\text{GEV}}\), can be written as [34].

\[
F_{\text{GEV}}(\text{NI} | \mu, \sigma, \gamma) = \exp \left\{ - \left[ 1 - \gamma \left( \frac{\text{NI} - \mu}{\sigma} \right) \right]^{-1/\gamma} \right\}, \quad -\gamma - \gamma (\text{NI} - \mu) \leq 0, \sigma > 0
\]

where \(\mu, \sigma\) and \(\gamma\) are location, scale and shape parameters of the GEV distribution, respectively. For the given NI values obtained from the entire scanned surface, a generalized weighted least square method, which solves a nonlinear optimization problem subject to multiple constrains, is utilized to estimate \(\mu, \sigma\) and \(\gamma\) parameters. More details on the parameter estimation are given in Park et al [35]. Once the statistical model of the NI values is established, a threshold value corresponding to a one-sided 99% confidence interval is obtained.

**Step V:** Finally, the DI values below the threshold are set to zero and only the ones above the threshold value are visualized by plotting them over the scanner surface.

4. Experimental validations

4.1. Fatigue tests

Two identical aluminum (6061-T6) plates shown in Fig. 3(a) were fabricated and micro-cracks and a macro-crack were introduced to Specimens I and II, respectively. To introduce micro and macro-cracks, Specimens I and II were subjected to \(4 \sim 40\) kN (\(R = 0.1\)) tensile cyclic.
Fig. 3. An aluminum plate specimen (Specimen II) and a macro-crack: (a) Geometry and dimensions of the specimen, and the configurations of ACTs for excitations, and (b) A 25 mm long macro-crack propagated from the center hole of Specimen II.

Fig. 4. Microscopic images of micro-cracks near the center hole of Specimen I.

Fig. 5. Microscopic images of the fatigue crack at the indented point [(a) and (b)] and the crack tip [(c) and (d)] of Specimen II. The numbers show crack widths at various locations.
loading with 10 Hz cycle rate using a universal testing machine (INSTRON 8801). After 50,000 cycles, a micro-crack was formed near the center hole of Specimen I. After 80,000 cycles, a 25 mm long macro-crack propagated from the center hole of Specimen II as shown in Fig. 3(b). Note that the macro-crack propagated in two directions both transverse to the loading direction. In particular, the macro-crack in the downward direction suddenly changed the propagation direction, producing an indented point as shown in Fig. 3(b).

Microscopic images of Specimens I and II were taken after tensile loading tests as shown in Figs. 4 and 5. In Fig. 4, the lengths and widths of micro-cracks near the center hole of Specimen I were observed to less than 60 μm and 1 μm, respectively. Fig. 5 presents microscopic images of the fatigue crack at the indented point and the crack tip. The width of the macro-crack in Specimen II was typically in the range of 1 ~ 40 μm, and micro-cracks at the indented point and the crack tip were also observed. Note that the crack width was often less than 1 μm near the indented point as shown in Fig. 5(b).

### 4.2. Experimental setup

To generate appropriate HF and LF sine waves, NCG200-D25-P76 and NCG50-S38 of Ultran Group are selected as ACTs 1 and 2, respectively, and their specifications are presented in Table 1. ACT 1 can generate sine waves within a frequency bandwidth of 140 kHz to 220 kHz, while ACT 2 can generate sine waves from 40 kHz to 70 kHz. ACT 1 is installed 76 mm apart from the specimen for focusing the HF input to a single circular point. On the other hand, non-focusing ACT with 38 mm × 38 mm square active area (ACT 2) was used for LF wave generation. ACT 2 was installed 30 mm apart from the specimen. Note that a large active area is selected for LF excitation due to reduced efficiency of ACT in a low frequency band (below 100 kHz).

Considering the BCs, the input frequencies are tuned to the resonance frequencies of the specimens for the generation of in-plane longitudinal (in-plane) modes, which are effective for crack opening-closing considering the fact that the through-thickness crack is introduced perpendicular to the wave propagation path between the excitation ACTs and the scan area. For specimen I, 45 kHz and 160 kHz were selected, and Q factors are 123 and 500, respectively. For specimen II, the resonance frequencies are 46 kHz and 156 kHz, and Q factors are 143 and 490, respectively. Digitally generated sine waves were converted to analog signals using a 1.28 MHz zero-holding digital-to-analog convert, and the analog input was applied to ACTs. The duration of the input signals was set long enough (409.6 ms) to guarantee the generation of stationary vibrations. To exert enough energy to the specimens, ± 50 V and ± 40 V were applied to ACTs 1 and 2, respectively.

A 3D LDV was installed 0.9 m apart from the specimen and ultrasonic responses were measured with a 1.28 MHz sampling rate. VD-07 10 mm/s/V internal decoder, which has a maximum sensitivity of 10 mm/s/V up to 350 kHz with 14-bit resolution, was used for velocity measurement. To improve the signal-to-noise ratio, the responses were measured 150 times and averaged in the time domain. The DI values are visualized for 20 mm × 20 mm square area with 1.2 mm spatial resolution (169 scan points) near the center hole of Specimens I and II as shown in Fig. 6(a) and (b) respectively. More specifically, a square area around the center hole is scanned for Specimen II while a square area below the center hole is scanned for Specimen I.

### 4.3. Fatigue crack visualization

The DI values obtained from the in-plane components of the measured ultrasonic responses are visualized for Specimens I and II as shown in Fig. 7. As for Specimen I, high DI values are observed near the center hole due to the formation of the micro-cracks (Fig. 7(a)). In particular, the location of the micro-cracks is better localized after denoising (Fig. 7(c)). Similar results are obtained for Specimen II (Fig. 7(b) and (d)). Here, it is noted that the highest DI values are observed near the indented point and the crack tip. The comparison between the previous microscopic images and the visualization results of Specimens I and II reveals that the largest nonlinear ultrasonic modulation occurred where the crack width is less than 1 μm. It is observed that the nonlinearity caused by a localized fatigue crack is larger than the background atomic nonlinearity. In particular, the highest nonlinearity is observed near the crack tip. The visualization results substantiate the hypothesis by Zaitsev stating that the nonlinearity mainly occurs due to micro-contacts at (1) micro-cracks prior to macro-crack formation, (2) macro-crack where the crack width is less than 1 μm and (3) micro-cracks near the macro-crack. Local plasticity is another potential source of nonlinear modulation. However, the plastic region was not clearly visualized in the presented experiments, probably due to the relatively small modulation produced by local plasticity compared to micro-contacts.

### Table 1

Specification of the ACTs used for ultrasonic excitation.

<table>
<thead>
<tr>
<th></th>
<th>ACT 1 (for HF excitation)</th>
<th>ACT 2 (for LF excitation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>NCG200-D25-P76</td>
<td>NCG50-S38</td>
</tr>
<tr>
<td>Active area</td>
<td>25 mm (circle)</td>
<td>38 mm × 38 mm (square)</td>
</tr>
<tr>
<td>Focus</td>
<td>Point focus (focal length 76 mm)</td>
<td>–</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>140–220 kHz</td>
<td>40–70 kHz</td>
</tr>
</tbody>
</table>

![Fig. 6](image-url) Scan area for fatigue crack visualization. (a) Specimen I and (b) Specimen II.
5. Conclusion

In this paper, a complete noncontact fatigue crack visualization technique based on nonlinear ultrasonic wave modulation is proposed. Two distinctive low frequency (LF) and high frequency (HF) inputs are applied to a structure using two air-coupled transducers (ACTs), and the corresponding ultrasonic responses are scanned over a target specimen using a 3D laser Doppler vibrometer (LDV). Then, the first sideband components at modulation frequencies are extracted and their amplitudes above a certain threshold value are visualized. The effectiveness of the proposed noncontact visualization technique for fatigue crack detection is tested using aluminum plates with different stages of fatigue crack formation. The micro and macro-cracks are successfully visualized by scanning the entire inspection area. The comparison of the experimental results and the microscopic images reveals that the modulation mainly occurs due to microcontacts at (1) micro-cracks prior to macro-crack formation, (2) macro-crack where the crack width is less than 1 μm and (3) micro-cracks near the macro-crack.

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