Reference-free fatigue crack detection using nonlinear ultrasonic modulation under various temperature and loading conditions

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\textbf{ABSTRACT}

This study presents a reference-free fatigue crack detection technique using nonlinear ultrasonic modulation. When low frequency (LF) and high frequency (HF) inputs generated by two surface-mounted lead zirconate titanate (PZT) transducers are applied to a structure, the presence of a fatigue crack can provide a mechanism for nonlinear ultrasonic modulation and create spectral sidebands around the frequency of the HF signal. The crack-induced spectral sidebands are isolated using a combination of linear response subtraction (LRS), synchronous demodulation (SD) and continuous wavelet transform (CWT) filtering. Then, a sequential outlier analysis is performed on the extracted sidebands to identify the crack presence without referring any baseline data obtained from the intact condition of the structure. Finally, the robustness of the proposed technique is demonstrated using actual test data obtained from simple aluminum plate and complex aircraft fitting-lug specimens under varying temperature and loading variations.

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1. Introduction

It is estimated that up to 90\% of failures of in-service metallic structures are attributed to fatigue cracks \cite{1}. Under repeated loading, unperceivable damage precursors such as dislocations or microcracks grow to fatigue cracks. The problem is that a fatigue crack often becomes conspicuous only after the crack reaches about 80\% of the total fatigue life for most metallic materials \cite{2}. Furthermore, a fatigue crack grown to a critical point at an alarming rate can lead to catastrophic consequences without any sufficient warning \cite{3}. For example, an undetected single fatigue crack in one of the train wheels resulted in the worst high-speed train derailment in history; the Eschede train disaster (1998, Germany) \cite{4}.

In this backdrop, nonlinear ultrasonic techniques, among other nondestructive (NDT) and structural health monitoring (SHM) techniques, have gained prominence for fatigue crack detection due to their higher sensitivity than linear techniques \cite{5,6}. Nonlinear ultrasonic techniques look for nonlinear characteristics of ultrasonic wave propagation such as harmonics and modulations (spectral sidebands) created by defects. One of the promising nonlinear techniques is nonlinear ultrasonic modulation in which mixing of two distinctive waves with different frequencies produces spectral sidebands at the sum and
difference between the two frequencies when the waves are propagating through a nonlinear mechanism such as a fatigue crack [7–11].

Nonlinear ultrasonic modulation with low frequency (LF) and high frequency (HF) signals is used to detect cracks in welded pipe joints in a nuclear power plant and cracks in concrete beams [12,13]. A fatigue crack in an aluminum plate is detected using a piezoelectric stack actuator for generation of a LF signal and a surface-mounted lead zirconate titanate (PZT) transducer for creation of a HF signal [14]. The usage of two surface mounted PZTs for generation of both LF and HF signals is investigated to detect bolt-loosening in aluminum plates and delamination in composites [15,16]. Fixed LF and swept HF signals are used to find an optimal combination of LF and HF signals that can amplify the modulation level [17].

In spite of recent developments in the nonlinear ultrasonic modulation techniques, there are still technical hurdles that need to be overcome before these techniques can make transitions to real SHM applications. This study attempts to tackle the following two particular issues. First, spectral sidebands generation are continuously altered by environmental and operational conditions of the target structure such as temperature and loading. The generation of spectral sidebands heavily depends on the dynamic characteristics of a host structure [17,18], and loading and temperature have significant influences on its dynamic characteristics [19–21]. Second, the existing nonlinear ultrasonic modulation techniques detect crack-induced sidebands by comparing the amplitudes of the spectral sidebands obtained from the baseline and damage conditions, but these techniques are susceptible to false alarms due to signal variations unrelated to the defect. For instance, the sideband amplitudes can simply vary due to changing temperature conditions.

In this study, a reference-free fatigue crack detection technique using nonlinear ultrasonic modulation is proposed so that a fatigue crack can be spotted at its early state even without relying on any baseline data obtained from the intact condition of a host structure. When two distinctive LF and HF inputs generated by surface-mounted PZT transducers are applied to the host structure, the presence of a fatigue crack can provide a mechanism for nonlinear ultrasonic modulation and create spectral sidebands around the frequency of the HF signal. A signal processing technique combining linear response subtraction (LRS), synchronous demodulation (SD) and continuous wavelet transform (CWT) filtering is developed to isolate the crack-induced spectral sidebands from measured ultrasonic signals. Then, a reference-free crack identifier based on a sequential outlier analysis is performed on the amplitudes of the first spectral sidebands for autonomous damage classification.

The uniqueness of this study lies in that (1) a reference-free crack detection technique, which does not rely on baseline signals obtained from the intact condition of a target structure, is developed first time based on nonlinear ultrasonic modulation; (2) the proposed technique is applied to detection of actual fatigue cracks in an aircraft fitting-lug with complex geometries as well as in a simple aluminum plate; and (3) the robustness of the proposed technique under temperature and loading variations is investigated.

This paper is organized as follows. The basic working principle of nonlinear ultrasonic modulation is briefly reviewed and the reference-free fatigue crack detection technique is proposed in Section 2. In Sections 3 and 4, the proposed crack detection technique is applied to detection of real fatigue cracks in aluminum plate and aircraft fitting-lug specimens under temperature and loading variations, respectively. Finally, the conclusion and discussions are provided in Section 5.

2. Theoretical development

2.1. Generation of nonlinear ultrasonic modulation

Consider two sinusoidal waves \( a \) and \( b \), where their frequencies are \( \omega_a < \omega_b \). When these waves propagate through a nonlinear region of a plate-like structure (e.g. fatigue crack), the solution for the total particle displacement, \( u_T \), can be written as the summation of the linear response, \( u_L \), harmonics, \( u_H \), and modulations \( u_S \) by solving the Navier equation with nonlinear boundary condition [17]:

\[
\begin{align*}
    u_T &= u_L + u_H + u_S \\
    \text{where} \\
    u_L &= u_a e^{-i \omega_a t} + u_b e^{-i \omega_b t} + \text{c.c.}, \\
    u_H &= u_{2a} e^{-i 2\omega_a t} + u_{2b} e^{-i 2\omega_b t} + \text{c.c.}, \\
    \text{and} \\
    u_S &= u_{a \pm b} e^{-i \omega_b \pm \omega_a t} + \text{c.c.}
\end{align*}
\]

where c.c. is complex conjugate, \( u_a \) and \( u_b \) are the amplitudes of the linear waves at \( \omega_a \) and \( \omega_b \), \( u_{2a} \) and \( u_{2b} \) are the amplitudes of the nonlinear harmonics at \( 2\omega_a \) and \( 2\omega_b \), and \( u_{a \pm b} = u_{b \pm a} + u_{b - a} \) is the amplitude of the first spectral sideband at \( \omega_b \pm \omega_a \) due to the mutual interaction of the LF and HF signals. Here, the higher order harmonics and modulations are omitted from the nonlinear solution for simplicity.

In early stage, it was thought that the opening and closing of crack due to cyclic loading was the main cause of the nonlinear modulation [9,10]. However, recently, it has been reported that the material dislocation, friction and stress concentration at the crack can also produce the modulation even at a very low strain level without crack opening and
Although the mechanism of nonlinear modulation has not been resolved yet, this finding at least suggests that the excitation levels of the input forces do not necessary have to be high enough to cause crack opening and closing.

Lima and Hamilton provide that the binding conditions that must be satisfied for the creation of the modulation due to a nonlinear mechanism theoretically and numerically [17]: (1) Synchronism (or phase matching): both the phase and group velocities of the linear waves must match with those of the modulated waves, and (2) non-zero power flux: the mode types of the linear and modulated waves should be identical (e.g. both are symmetric or both anti-symmetric), thus ensuring non-zero power transfer from the linear waves to the modulated waves. Moreover, Yoder and Adams experimentally show that the modulated wave amplitude is also dependent on the frequency response function of a structure [18]. It is demonstrated that, when one of the modulated frequencies, $\omega_b \pm \omega_a$, coincides with one of the resonance frequencies of the structure, the amplitude of that particular spectral sideband is magnified.

### 2.2. Extraction of first spectral sidebands using LRS, SD and CWT

The response signal obtained by simultaneous application of LF and HF inputs to a host structure is presented in Fig. 1 (a) with the assumption of nonlinear mechanism present. The solid and dotted lines are the linear and nonlinear responses, respectively. Generally, the amplitude of the nonlinear response is several orders of magnitude smaller than that of the linear response. However, because the proposed fatigue crack detection technique focuses on the nonlinear modulation components, particularly the first spectral sideband, a combination of LRS and SD techniques is developed to isolate only the first spectral sideband component.

**Fig. 1.** Overview of the proposed first spectral sideband extraction technique: (a) frequency domain representation of the response signal obtained by simultaneous applications of the low frequency (LF) and high frequency (HF) inputs with the presence of a nonlinear mechanism, (b) superposition of two response signals obtained by individual applications of the LF and HF inputs, (c) extraction of the sideband components using the proposed linear response subtraction (LRS) by subtracting the signal in (b) from the one in (a), (d) extraction of only the first spectral sideband component using synchronous demodulation (SD) and continuous wavelet transform (CWT) filtering. SD brings down the first spectral sideband component relative to the DC frequency rather than the frequency of the HF signal and CWT isolates only the first spectral sideband component.
First, two separate response signals are obtained by independently applying the LF and HF inputs to the structure. Then, the LRS extracts the spectral sideband components simply by subtracting the summation of these two signals shown in Fig. 1(b) from the response signal obtained by the simultaneous excitation of the LF and HF inputs as shown in Fig. 1(a). Fig. 1(c) shows that the resulting signal contains only the spectral sideband components \( \mathbf{u}_S \). The advantage of LRS is that the nonlinear harmonics, \( \mathbf{u}_H \), as well as the linear response, \( \mathbf{u}_L \), are removed during LRS, and only the spectral sideband component is retained:

\[
\mathbf{u}_S = \mathbf{u}_L \pm \mathbf{u}_H e^{-2i\omega_b t} + \alpha(\mathbf{u}_L + \mathbf{u}_H) + \text{c.c.}, \quad \alpha \approx 0
\]  

(5)

In practice, because the magnitudes of the linear response components are much larger than those of the spectral sideband components, these linear components, shown as \( \alpha \mathbf{u}_L \), in Eq. (5) cannot be fully eliminated using LRS. Furthermore, the residual harmonic terms denoted as \( \alpha \mathbf{u}_H \) also remain.

Then, SD is employed to bring down the first spectral sideband component relative to the DC frequency rather than the frequency of the HF signal as shown in Fig. 1(d). For this, the previously obtained \( \mathbf{u}_S \) is multiplied by a local oscillator with unit amplitude, \( L = e^{-i\omega_1 t} \) [22–24]. In this study, the HF input signal is used as the local oscillator.

\[
\mathbf{u}_S = \mathbf{u}_L \pm \mathbf{u}_H e^{-2i\omega_b t} + \alpha(\mathbf{u}_L + \mathbf{u}_H) + \text{c.c.}
\]  

(6)

Note that, because our interest is the first sideband component, CWT filtering is applied to isolate only this component only at \( \omega_2 \) [25].

\[
\mathbf{u}_S = \frac{1}{\sqrt{|s|}} \int \mathbf{u}_S \psi^* \left( \frac{t-t}{s} \right) dt + \text{c.c.}
\]  

(7)

where \( \mathbf{u}_S \), \( \psi^*(t) \), \( s \) and \( t \) are the first spectral sideband component, the mother wavelet, scaling and translation, respectively. Here, the \( s \) value is set to the one corresponding to the frequency of the LF signal.

2.3. Reference-free damage detection using a sequential outlier analysis

As discussed in Section 2.1, the spectral sidebands are generated only at specific combinations of LF and HF signals even at the presence of nonlinear mechanism, and the optimal frequency combinations of LF and HF signals will change over time for field applications due to operational and environmental variations. In this study, the frequencies of LF and HF signals are swept over certain ranges to increase the detectability of the first spectral sidebands.

Step 1: a sinusoidal LF input and a linear chirp HF input with a certain frequency range is applied to the structure. Step 2: \( \mathbf{u}_S \) corresponding to a certain LF is obtained from Eq. (7) and the standard deviation of \( \mathbf{u}_S \) is defined as a nonlinear index (NI).

\[
\text{NI} = \text{std} (\mathbf{u}_S)
\]  

(8)

Step 3: steps 1 and 2 are repeated by stepping the frequency of LF signal from an initial to final value with a constant increment while the frequency range of HF signal is fixed. Step 4: a sequential outlier analysis is applied from all the stepping LF signals. The proposed sequential outlier analysis operates based on the premise that the prominent sidebands, the NI values in this case, are observed only at certain LF value. The procedure of the sequential outlier analysis can be summarized as follows [26,27].

1. Arrange all NI values obtained from the stepping LF signals in an ascending order.
2. Fit a parametric distribution to the \( n - 1 \) smallest NI values and compute a threshold value corresponding to a user specified confidence level. Here, it is assumed that there are no outliers (significant first sideband) among the \( n - 1 \) smallest NI values.
3. If the value of the \( n \)th smallest NI value is larger than the threshold value, the NI values larger than the \( n \)th NI value are determined to be outliers (indication of nonlinear mechanism). If not, repeat steps (2) and (3) for the next smallest value \( n + 1 \) until the largest NI value is tested.

3. Crack detection in an aluminum plate

3.1. Experimental setup

Two identical aluminum plate specimens were fabricated from 7075-T351 aluminum alloy commonly used in aircraft applications. The geometry and dimensions of the plate specimen are presented in Fig. 2(a). Four identical lead zirconate titanate (PZT) transducers with 6.35 mm diameter and 0.254 mm thickness manufactured by APC International were installed on each specimen. Two PZTs labeled as ACT 1 and ACT 2 are used for generation of LF and HF signals, and the other two denoted as SEN 1 and SEN 2 for sensing. A 35 mm long fatigue crack was introduced to one of the specimens through cyclic loading tests (Fig. 2(b)) [28].

In this study, a NI PXI data acquisition system consists of two arbitrary waveform generators (AWGs, NI PXI-5421) and a 2-channel high speed digitizer (DIG, NI PXI-5122) was used. Fig. 3 shows the schematic diagram of the experimental setup.
AWG 1 is used for generation of a linear chirp HF input at ACT 1, and AWG 2 for exertion of a sinusoidal LF input at ACT 2. Both input signals were converted to analog inputs with 2 MHz zero-holding conversion rate and had a peak-to-peak voltage of ± 10 V. The output responses from SEN 1 and SEN 2 were simultaneously measured using DIG at a sampling rate of 2 MHz for 0.5 s. The AWGs and DIG were synchronized and controlled by LabVIEW software. To improve the signal-to-noise ratio, the responses were measured 10 times and averaged in the time domain. The LF and HF ranges were determined considering the effective frequency range for PZT operation, the specification of the DAQ system used, the noise spectrum over the frequency ranges.

For the temperature test, the specimens were placed inside a temperature chamber and the signals were obtained under four other temperature conditions (−15, 0, 30 and 45 °C). The temperature of the chamber was maintained within 1 °C accuracy during the data acquisition. For the ambient vibration test, random excitations with different maximum peak amplitudes were introduced to the specimens by a mechanical shaker. The frequency range of the random excitation was 0–50 Hz. The peak amplitudes were measured using an accelerometer installed on the specimens and the temperature was maintained at room temperature (15 °C).

3.2. Experimental results

Fig. 4(a) and (b) shows the raw time signals obtained from SEN 1 of the intact (Fig. 4(a)) and damage (Fig. 4(b)) specimens by concurrently applying a 80–110 kHz linear chirp signal to ACT 1 and 17 kHz sine signal to ACT 2. Here, in Fig. 4(a) and (b), LF, HF, harmonics and modulated signals are combined together as shown in Fig. 1(a). After LRS, the first spectral sideband signal become noticeable for the crack case in Fig. 4(d), while there is no sign of the modulated signal for the intact case in Fig. 4(c). However, the linear response components are not fully removed and still present in the signals shown in Fig. 4(c) and (d) due to the incompleteness of LRS as shown in Fig. 1(c). The presence of the undesired linear components are further alleviated using SD and CWT in Fig. 4(e) and (f). A “Morlet” wavelet is used for the CWT filtering. Indeed, other wavelets such as Haar, Daubechies, Biorthogonal, Meyer and Gaussian were also tested, and similar results are obtained. Therefore, only representative results using the Morlet wavelet are presented in this study. Finally, the first spectral sideband clearly appears for the crack case in Fig. 4(f), and no such component stands out for the intact case in Fig. 4(e).

Fig. 5(a) shows the NI values obtained from SEN 1 of the intact specimen by stepping the frequency of the LF input from 10–20 kHz with a 250 Hz increment and using a linear chirp HF input in the range of 80–110 kHz. A total of 41 NI values corresponding to 41 incremental LF values are computed according to Eq. (8). The NI values shown in Fig. 5(b) are obtained by repeating the same procedure using the data acquired from the damage specimen.

The NI values in Fig. 5(a) and (b) are sorted in an ascending order as shown in Fig. 5(c) and (d) and the sequential outlier analysis is conducted. Assuming that first half of the sorted NI values (in this case, 20) do not represent the presence of nonlinear mechanism, a threshold value corresponding to a one-side 99.99% confidence interval is established by fitting a normal distribution to the 20 smallest NI values. For the calculation of the threshold value, a reasonable number of NI values are necessary. Moreover, because the sideband components are generated only at specific frequency combinations of LF and HF, it is important to have a sufficient number of data points for accurate determination of the threshold value.

Fig. 4. Extraction of the first spectral sideband component using a combination of LRS, SD and CWT: (a) and (b) show the raw time signals obtained from SEN 1 of the intact and damaged specimens. (c) and (d) show the signals obtained after applying LRS to the signals in (a) and (b). The signals shown in (e) and (f) are obtained after applying SD and CWT to the signals in (c) and (d).

Fig. 5. Sequential outlier analysis using the responses obtained from the plate specimen at SEN 1: (a) and (b) show the NI values obtained from the intact and damaged specimens by stepping the frequency of the LF input from 10–20 kHz with a 250 Hz increment and using a linear chirp HF input from 80–110 kHz. In (c) and (d), the NI values in (a) and (b) are sorted in an ascending order for the sequential outlier analysis, and about 20% of NI values are classified as outliers for the damage case.
HF inputs, it is safe to assume that the number of outliers is limited (less than half). Then, the sequential outlier analysis is performed on the 21st smallest NI value to determine if the 21st smallest NI is an outlier with respect to the 20 smallest NI values. If the 21st NI value becomes larger than the threshold value, it is concluded that there is nonlinear mechanism. If not, the sequential outlier analysis proceeds to the next smallest NI value until the largest NI value is reached. Eight NI values (about 20%) out of 41 are classified as outliers for the damage case, while no outlier is detected for the intact case. In Fig. 6, a similar trend is obtained when the signals measured from SEN 2 are used.

In real applications, structures are often subject to changing surrounding conditions such as temperature and external loading variations that can adversely affect measured signals. In Fig. 7, for example, the LF values corresponding to the significant first spectral sideband amplitudes vary due to temperature and loading conditions. The damage detection results under varying temperature and ambient vibration conditions are summarized in Tables 1 and 2, respectively. Similar to the previous experiment conducted at room temperature (15°C), no false alarm is observed for the intact case, and the fatigue crack is successfully identified for the damage case under all investigated temperature and loading conditions.

4. Crack detection in an aircraft fitting-lug

Two mock-up specimens, which represent a fitting-lug connecting an aircraft wing to a main fuselage frame, were fabricated from 6061-T6 aluminum alloy as shown in Fig. 8. Three identical dual PZTs manufactured by Metis Design were installed to each specimen around the crack prone location as shown in Fig. 8. Each dual PZT consists of two concentric inner circle and outer ring segments, and the dual PZT is packaged by a Kapton tape with printed circuit and two SMA connectors [29]. The outer and inner diameters of the ring segment, the diameter of the inner circular PZT segment, and the thickness of the dual PZT are 18 mm, 10 mm, 8 mm and 0.3 mm, respectively. One PZT was used as an actuator (ACT), and the others as sensors (SEN 1 and SEN 2). Here, unlike the previous experiment, a single dual PZT was used for exerting both LF and HF inputs. A sine LF signal was applied to the outer ring, and a linear chirp HF signal to the inner circle segment of ACT, respectively. Corresponding responses were measured using the inner circle parts of SEN 1 and SEN 2. In the previous research, it is known that a larger PZT size is preferred for excitation while a smaller size is more advantageous for sensing [30]. A 40 mm long fatigue crack was introduced to one of the specimens in Fig. 9 by applying cyclic loading as shown in Fig. 10(a). During fatigue testing, 10 blocks of the loading spectrum in Fig. 10(b) (2500 cycles) were applied at the tip of the beam to generate stress in the fitting-lug. According to current aircraft design specifications, this loading is equivalent to real operational loading corresponding to 1000 flight hours. This is a typical duration of flight hours used for fatigue evaluation at US Air Force, and an actual loading history measured from an actual aircraft [31]. The rest of the test setup and the conditions for the temperature and loading tests were identical to the previous plate experiment.

Tables 3 and 4 show the damage detection results obtained from the fitting-lug specimens under temperature and loading variations. Similar to the plate specimen tests, the outliers are observed only from the damage case, while no outlier is observed from the intact case. Therefore, the fatigue crack is successfully detected and no false-alarms were triggered due to temperature and loading variations.


Fig. 6. Damage detection results obtained from the plate specimen at SEN 2: (a) and (b) show the NI values obtained from the intact and damaged specimens by stepping the frequency of the LF input from 10 to 20 kHz with a 250 Hz increment and using a linear chirp HF input from 80 to 110 kHz. In (c) and (d), the NI values in (a) and (b) are sorted in an ascending order for the sequential outlier analysis, and about 20% of NI values are classified as outliers for the damage case.
5. Conclusions

In this study, a reference-free fatigue crack detection technique using nonlinear ultrasonic wave modulation is developed. Surface-mounted lead zirconate titanate (PZT) transducers are used for the generation of two distinctive low frequency (LF) and high frequency (HF) inputs. The first spectral sideband, which is the nonlinear modulation component around the frequency of the HF input and generated by the presence of a nonlinear mechanism such as a fatigue crack, is isolated and explored. A signal processing technique combining linear response subtraction (LRS), synchronous modulation (SD) and continuous wavelet transform (CWT) is developed to extract the first spectral sideband component from measured ultrasonic signals. First, the linear response components as well as harmonics are removed from the measured responses.

Fig. 7. NI values obtained from SEN 1 of the intact and damaged specimens subject to temperature and loading variations: (a) and (b) are from the intact and damaged specimens at -15°C, (c) and (d) are from 45°C, (e) and (f) are obtained with a random excitation of 2.0 g peak amplitude and 0–50 Hz frequency range. The peak amplitude was measured using an accelerometer installed on the plate specimens and the temperature was maintained at room temperature (15°C).

Table 1
Damage diagnosis of plate specimens under temperature variations.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Sensor</th>
<th>No. of outliers (%) out of 41 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Intact</td>
</tr>
<tr>
<td>-15°C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>0°C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>30°C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>45°C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
</tbody>
</table>

5. Conclusions

In this study, a reference-free fatigue crack detection technique using nonlinear ultrasonic wave modulation is developed. Surface-mounted lead zirconate titanate (PZT) transducers are used for the generation of two distinctive low frequency (LF) and high frequency (HF) inputs. The first spectral sideband, which is the nonlinear modulation component around the frequency of the HF input and generated by the presence of a nonlinear mechanism such as a fatigue crack, is isolated and explored. A signal processing technique combining linear response subtraction (LRS), synchronous modulation (SD) and continuous wavelet transform (CWT) is developed to extract the first spectral sideband component from measured ultrasonic signals. First, the linear response components as well as harmonics are removed from the measured responses.

Table 2
Damage diagnosis of plate specimens under loading variations.

<table>
<thead>
<tr>
<th>Peak acc.</th>
<th>Sensor</th>
<th>No. of outliers (%) out of 41 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Intact</td>
</tr>
<tr>
<td>2.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>2.5 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>3.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>3.5 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>4.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
</tbody>
</table>

Fig. 8. A mock-up specimen representing a fitting-lug connecting an aircraft wing to a main fuselage frame.

Fig. 9. A 40 mm long fatigue crack was introduced to one of the specimens by applying cyclic loading.

Fig. 10. Fatigue test for the fitting-lug specimen. (a) Fatigue test configuration. (b) One block (250 cycles) loading spectrum applied to the fitting-lug.
using the LRS technique. Next, the first spectral sideband component is isolated from the remaining modulation components using a combination of SD and CWT. Then, a nonlinear index (NI) is defined as the standard deviation of the first spectral sideband component. Finally, a reference-free fatigue crack classifier is developed considering the amplitude of the first spectral sideband component over a wide range frequency of LF and HF signals. A sequential outlier analysis is performed on the NI values corresponding to a wide frequency range of LF and HF inputs with the premise that the nonlinear mechanism will be identified only at certain frequency combination of LF and HF inputs. It is demonstrated that real fatigue cracks in complex metallic structures can be reliably detected even under various temperature and loading conditions without using baseline data from the intact condition of the structure.

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References


Table 3
Damage diagnosis of fitting-lug specimen under temperature variations.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Sensor</th>
<th>No. of outliers (ratio, %) out of 41 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>–15 °C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>0 °C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>15 °C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>30 °C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>45 °C</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
</tbody>
</table>

Intact  Damage
7 (17.07) 6 (15.00)
8 (19.51) 7 (17.07)
12 (29.27) 11 (27.06)
5 (12.00) 5 (12.00)
7 (17.07) 7 (17.07)
7 (17.07) 7 (17.07)
2 (4.88) 2 (4.88)
3 (7.31) 3 (7.31)
13 (31.71) 13 (31.71)

Table 4
Damage diagnosis of fitting-lug specimen under loading variations.

<table>
<thead>
<tr>
<th>Peak acc.</th>
<th>Sensor</th>
<th>No. of outliers (ratio, %) out of 41 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>2.5 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>3.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>3.5 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td>4.0 g</td>
<td>SEN 1</td>
<td>0 (0.00)</td>
</tr>
<tr>
<td></td>
<td>SEN 2</td>
<td>0 (0.00)</td>
</tr>
</tbody>
</table>

Intact  Damage
6 (14.63) 6 (14.63)
7 (17.07) 7 (17.07)
9 (21.95) 9 (21.95)
8 (19.51) 8 (19.51)
8 (19.51) 8 (19.51)
8 (19.51) 8 (19.51)
10 (24.39) 10 (24.39)


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