Nonlinear ultrasonic wave modulation for online fatigue crack detection

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ABSTRACT

This study presents a fatigue crack detection technique using nonlinear ultrasonic wave modulation. Ultrasonic waves at two distinctive driving frequencies are generated and corresponding ultrasonic responses are measured using permanently installed lead zirconate titanate (PZT) transducers with a potential for continuous monitoring. Here, the input signal at the lower driving frequency is often referred to as a ‘pumping’ signal, and the higher frequency input is referred to as a ‘probing’ signal. The presence of a system nonlinearity, such as a crack formation, can provide a mechanism for nonlinear wave modulation, and create spectral sidebands around the frequency of the probing signal. A signal processing technique combining linear response subtraction (LRS) and synchronous demodulation (SD) is developed specifically to extract the crack-induced spectral sidebands. The proposed crack detection method is successfully applied to identify actual fatigue cracks grown in metallic plate and complex fitting-lug specimens. Finally, the effect of pumping and probing frequencies on the amplitude of the first spectral sideband is investigated using the first sideband spectrogram (FSS) obtained by sweeping both pumping and probing signals over specified frequency ranges.

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1. Introduction

A crack is one of the primary culprits for the failure of metallic structures. It is estimated that up to 90 percent of failures of in-service metallic structures are the result of fatigue cracks [1]. A fatigue crack is initiated from a damage precursor at unperceivable level (e.g. dislocation or micro crack in materials) when the material is subjected to repeated loading. The precursor can often continue to grow to a critical point at an alarming rate without sufficient warning, leading to catastrophic consequences [2]. That is, a fatigue crack often becomes conspicuous only after the crack reaches about 80 percent of the total fatigue life for most metallic materials [3]. For example, the Eschede train disaster (1998, Germany), the worst high-speed train derailment in history, occurred because a single fatigue crack in one of the train wheels went undetected and finally failed [4].

In this backdrop, ultrasonic techniques, among other nondestructive (NDT) and structural health monitoring (SHM) techniques, have gained prominence for online fatigue crack detection due to their immense potential in periodic and
continuous monitoring of in-service structures and their relatively large sensing range. The conventional techniques often rely on the linear property modifications of ultrasonic waves near a defect, such as reflection, attenuation, mode conversion etc., for crack detection. However, these linear features are reported to be not sensitive enough to detect fatigue cracks until they become visibly large [5].

To tackle the limitation of these linear techniques, a body of research has gone into the development of nonlinear ultrasonic techniques, which look for nonlinear characteristics such as harmonics and modulations (spectral sidebands) created by defects. The sensitivity of the nonlinear ultrasonic techniques to defects has been shown to be far better than that of the linear ones [6–7]. One of the promising nonlinear techniques is nonlinear modulation, also known as vibro-acoustic modulation (VAM) [8–9]. When two sinusoidal signals at distinctive frequencies are propagating through a medium that has a nonlinear mechanism such as a crack, the mixing of these two propagating waves produces spectral sidebands at the sum and difference between the two frequencies. Here, the lower frequency input is often referred to as a ‘pumping’ signal, and the higher frequency input as a ‘probing’ signal. The spectral sidebands can be found at the probing frequency plus and minus the pumping frequency.

Initially, it was thought that crack opening and closing was the main cause of such nonlinear modulation [10–11]. However, it has been recently shown that the dislocation, friction, stress concentration and temperature gradient due to the crack can also produce nonlinear modulation even at a very low strain level without crack opening and closing [12–13]. Although the full mechanism of the nonlinear modulation has not been resolved yet, this finding at least suggests that (1) a fatigue crack can be detected even before it grows to an open crack and (2) the excitation levels of the input forces do not necessary have to be high enough to cause crack opening and closing.

VAM with a low-frequency pumping signal and a high-frequency probing signal is used to detect cracks in welded pipe joints in a nuclear power plant and cracks in concrete beams [14–15]. A fatigue crack in an aluminum plate was detected using a piezoelectric stack actuator to generate a pumping signal lower than 1 kHz and a permanently installed lead zirconate titanate (PZT) transducer to create a probing signal around 60 kHz [16]. Fixed frequency pumping and swept frequency probing signals are used to find an optimal combination of the probing and pumping frequencies that can amplify the modulation level [17]. Here, a fixed frequency pumping signal lower than 500 Hz is generated by a mechanical shaker, and a swept frequency probing signal from 20 to 60 kHz is produced by a piezoelectric stack actuator. The usage of two permanently installed PZT transducers for generation of both pumping and probing signals is investigated to detect bolt-loosening in aluminum plates and delamination in composites [18–19]. A ±400 V pumping signal below 2 kHz and a ±10 V probing signal around 30–750 kHz were used. Note that a very high voltage pumping signal is used here.

In this study, a fatigue crack detection technique is developed based on nonlinear ultrasonic wave modulation so that in-service metallic structures can be monitored for potential fatigue damage. In comparison with the aforementioned literature, the uniqueness of this study lies in that (1) permanently installed PZT transducers are used to generate low-amplitude, around ±10 V, ultrasonic pumping and probing signals above 10 kHz with a potential for continuous monitoring, (2) a spectral sideband extraction technique combining linear response subtraction (LRS) and synchronous demodulation (SD) is developed so that only crack-induced spectral sidebands can be extracted, (3) a spectrogram – named the first sideband spectrogram (FSS) – is constructed to identify the best combinations of the probing and pumping frequencies that amplify the crack-induced spectral sideband amplitudes, and (4) the proposed fatigue crack detection technique is applied to detect an actual fatigue crack in an aircraft fitting-lug with complex geometries as well as in a simple aluminum plate.

This paper is organized as follows. In Section 2, the basic working principle of nonlinear wave modulation is briefly reviewed and a spectral sideband extraction technique is proposed. Then, the proposed crack detection technique is applied to detect actual fatigue cracks in an aluminum plate and an aircraft fitting-lug specimen in Sections 3 and 4, respectively. Finally, the conclusion and discussions are provided in Section 5.

2. Theoretical development of a first sideband extraction technique

2.1. Basic working principle of nonlinear wave modulation

When two waves $a$ and $b$, at distinctive frequencies $\omega_a$ and $\omega_b$ ($\omega_a < \omega_b$), propagate through a nonlinear region of a plate-like structure in the $z$-direction, the solution for the total particle displacement, $u^T$, can be written as the summation of the linear response, $u^{(1)}$, harmonics, $u^{(2)}$, and modulations $u^{(3)}$, as follows [12]:

$$u^T = u^{(1)} + u^{(2)} + u^{(3)}$$

(1)

where

$$u^{(1)} = a_1 e^{i(\omega_1 z - \omega_1 t + \phi_1)} + a_2 e^{i(\omega_2 z - \omega_2 t + \phi_2)} + \text{c.c}$$

(2)

$$u^{(2)} = a_2 e^{i(\omega_1 z - \omega_1 t + \phi_1)} + a_2 e^{i(\omega_2 z - \omega_2 t + \phi_2)} + \text{c.c}$$

(3)

and

$$u^{(3)} = a_2 e^{i(\omega_1 z + \omega_2 z - (\omega_1 \pm \omega_2) t + (\phi_1 \pm \phi_2)) + \text{c.c}$$

(4)
where $c.c$ stands for 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 $u_{a+b} = u_{b+a} = u_{b-a}$ is the amplitude of the first spectral sideband, the modulation responses at $\pm \omega_a$ about the probing frequency $\omega_b$, due to the mutual interaction of the linear waves, $\kappa_a$ and $\kappa_b$ and $\theta_a$ and $\theta_b$ are the wavenumbers and phases corresponding to waves $a$ and $b$, respectively. Note that, for simplicity, the higher-order harmonics and modulations are omitted here from the nonlinear solution. The complete nonlinear solution and the detailed descriptions of $u_a$, $u_b$, and $u_{a+b}$ can be found in [20].

The particle velocity of the first spectral sideband, $\mathbf{v}^{(3)} = \frac{\partial u^{(3)}}{\partial t}$, can be represented as a linear combination of the waveguide modes of the plate-like structure at $\omega_b \pm \omega_a$:

$$\mathbf{v}_{b \pm a}(y, z, t) = \frac{1}{\sqrt{2}} \sum_{m=1}^{\infty} A_{m \pm} (z) e^{i(\omega_m \pm \omega_0) t} + c.c.$$

where $y$ is in the direction of the plate thickness measured from the plate center, and $A_{m \pm}$ and $\mathbf{v}_{m \pm}$ are the modal amplitude and particle velocity of the $m$th mode at $\omega_b \pm \omega_a$, respectively. $A_{m \pm}$ is determined as [21]

$$A_{m \pm}(z) = \bar{A}_{m \pm}(z) e^{i(\kappa_m \pm \kappa_a) y} - \bar{A}_{m \pm}(0) e^{i\kappa_a y}$$

where

$$\bar{A}_{m \pm}(z) = \frac{4 P_{mn \pm} |z|^{\kappa_a - \kappa_m} e^{i\kappa_m y}}{4 P_{mn \pm} + f_{n \pm}^{vol} + f_{n \pm}^{surf}}$$

and

$$A_{m \pm}(z) = \frac{4 P_{mn \pm} |z|^{\kappa_a - \kappa_m} e^{i\kappa_m y}}{4 P_{mn \pm} + f_{n \pm}^{vol} + f_{n \pm}^{surf}}$$

where $\kappa_{n \pm}$ is the wavenumber of the $n$th mode, which is not orthogonal to the $m$th mode, $P_{mn \pm}$ is the complex power flux of the $m$th mode at $\omega_b \pm \omega_a$, along the $z$-direction, and $f_{n \pm}^{vol}$ and $f_{n \pm}^{surf}$ are the complex power fluxes of the linear waves through the volume and surface, respectively.

Eqs. (7) and (8) provide the binding conditions that must be satisfied for the creation of the modulated waves due to a nonlinear mechanism theoretically and numerically [12]: (1) Synchronism (or phase matching), $\kappa_{n \pm} = (\kappa_m \pm \kappa_a)$: both the phase and group velocities of the linear waves must match with those of the modulated waves, and (2) non-zero power flux, $f_{n \pm}^{vol} + f_{n \pm}^{surf} \neq 0$: 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. The same conditions also can be applied to nonlinear harmonics when $\omega_a = \omega_b$ and $\kappa_a = \kappa_b$, and the conditions were validated experimentally even for a single localized fatigue crack [2,22]. Moreover, Yoder and Adams experimentally show that the modulated wave amplitude, $\bar{A}_{m \pm}(z)$, is also dependent on the frequency response function of a structure [17]. 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 the first spectral sideband signal

The response signal obtained by simultaneously applying both probing and pumping inputs to the host structure is presented in Fig. 1(a) by assuming the presence of nonlinear mechanism. The solid and dotted lines denote the linear and nonlinear responses, respectively. Typically, the amplitude of the nonlinear response is several orders of magnitude smaller than that of the linear response, but the proposed fatigue crack detection technique relies on the nonlinear component for damage detection, particularly the first spectral sideband component. Therefore, to isolate only the first spectral sideband component, a signal processing technique combining LRS and SD is developed.

First, two separate response signals are obtained by independently applying the probing and pumping signals. Then, the LRS extracts the spectral sideband components simply by subtracting the summation of these two signals in the time domain shown in Fig. 1(b) from the response signal corresponding to the simultaneous excitation of the pumping and probing inputs in Fig. 1(a). Fig. 1(c) shows the resulting signal, which, in theory, contains only the spectral sideband components. One advantage of LRS is that the harmonics of the pumping and probing signals are also removed, and only the spectral sideband signal is retained:

$$u_{b \pm a}(y, z, t) = u_b \pm a e^{i(\kappa_b + \kappa_a) y} - (e^{i(\omega_b + \omega_a) t} + e^{i(\theta_b + \theta_a)}) + a u^{(1)} + a u^{(2)} + c.c. \quad a \approx 0$$

Note that, because the magnitudes of the linear response components are much larger than those of the spectral sideband components, these linear components cannot be fully eliminated using LRS as shown in terms of $au^{(1)}$ in Eq. (9). Furthermore, the residual harmonic terms are shown as $au^{(2)}$.

Next, SD is employed to isolate only the first spectral sideband component out of $u_{b \pm a}$ and bring it down relative to the DC frequency rather than the probing frequency. To extract the first spectral sideband component, the previously obtained $u_{b \pm a}$ is multiplied by a local oscillator with unit amplitude, $L = e^{i(\omega - \omega_b + \theta_b)}$ [23–25]. In our study, the input probing signal is used as
the local oscillator.

\[
\tilde{u}^{(3)}_b = u_b e^{i \omega_b t} + \sum_{k_a, k_b} \gamma_k e^{i \left( (\omega_b + \omega_a) t + \beta_k t + \theta_k \right)} + \frac{\alpha}{\cos(\omega_a t)} + \frac{\beta}{\cos(\omega_b t)} + c.c.
\] (10)

Note that the first spectral sideband of our interest is only the \( u_{b+a} \) component at \( \omega_a \). To remove other response at higher and DC frequency values, a band-pass filter with cut-off frequencies of \( \omega_{l_c} \) and \( \omega_{u_c} \) is applied to Eq. (10):

\[
\omega_{l_c} < \omega_a \quad \text{and} \quad \omega_a < \omega_{u_c} - \omega_b - \omega_a
\] (11)

Finally, the first spectral sideband component extracted from \( \tilde{u}^{(3)}_b \) becomes

\[
\tilde{u}^{(3)}_b = u_b e^{i \omega_b t} + \sum_{k_a, k_b} \gamma_k e^{i \left( (\omega_b + \omega_a) t + \beta_k t + \theta_k \right)} + c.c.
\] (12)

A fatigue crack is identified by comparing the amplitudes of the first spectral sideband components extracted from the intact and damage cases.

3. Crack detection in an aluminum dog-bone

3.1. Experimental setup

Two identical dog-bone specimens with a hole at the center were fabricated using 7075-T351 aluminum alloy that is commonly used in aircraft applications. The geometry and dimensions of the dog-bone specimen are shown in Fig. 2(a). A 35 mm-long fatigue crack was introduced to one of the dog-bone specimens through cyclic loading tests (Fig. 2(b)). An MTS machine with a 10 Hz cycle rate, a maximum load of 64.6 kN and a stress ratio \( R = 0.1 \) was used for the fatigue test. Details on the fatigue test are presented in [26]. Four identical PZTs manufactured by APC International were permanently installed on each specimen using epoxy, as shown in Fig. 2(a). Each PZT has a diameter of 6.35 mm and a thickness of 0.254 mm. Two PZTs labeled as ACT 1 and ACT 2 are used for the generation of ultrasonic waves, and the other two denoted as SEN 1 and SEN 2 for sensing.

The data acquisition system (NI PXI) used in this study consists of two arbitrary waveform generators (AWGs, NI PXI-5421), a 2-channel 14-bit high-speed digitizer (DIG, NI PXI-5122). The schematic diagram of the experimental setup is presented in Fig. 3. AWG 1 was used to generate a linear chirp probing signal (i.e., the frequency increases linearly with time) applied to ACT 1 and AWG 2 to generate a sinusoidal pumping signal at ACT 2. Both input signals had a peak-to-peak voltage of \( \pm 10 \) V, and they were converted to analog input signals at a conversion rate of 2 MHz with zero-order holding. 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. The responses were measured 10 times and averaged in the time domain to improve the signal-to-noise ratio.

3.2. Validation of the proposed first spectral sideband extraction technique

Fig. 4(a) and (b) shows the Short Time Fourier Transform (STFT) of the raw time signals obtained from SEN 1 by applying a sine pumping at 16.5 kHz and a linear chirp probing from 80 to 110 kHz. There is no discernible difference between the raw signals obtained from the intact (Fig. 4(a)) and damaged (Fig. 4(b)) specimens. The dynamic range of DIG is set at 0.4 V considering the maximum amplitude of the response signals. Here, the modulated spectral sidebands associated with the
crack case are invisible because the amplitudes of the pumping and probing signals are much more dominant than those of the sidebands. The largest sideband amplitude is observed at a frequency combination of pumping at 16.5 kHz and probing at 86.0 kHz, and the amplitudes of the linear responses at pumping and probing frequencies are $-99.8$ dB and $-47.6$ dB, respectively. The amplitudes of the second harmonics at 33 kHz and 172 kHz are $-124.7$ dB and $-74.6$ dB, respectively. The amplitude of the first sideband at 69.5 (86.0−16.5) kHz is $-120.6$ dB, whereas the noise level around the sideband is $-140.5$ dB. The existence of the harmonics of the probing signal is not shown here owing to the limited frequency range of the plot.

After applying LRS, the spectral sidebands become noticeable for the crack case in Fig. 4(d), although there is no sign of the spectral sidebands for the intact case in Fig. 4(c). However, the linear response at the probing frequency still persists because LRS is not perfect and cannot fully get rid of the linear response component. The amplitudes of the residual pumping and probing signals are reduced to $-134.4$ dB and $-119.0$ dB, respectively, and the second harmonic amplitudes to $-139.6$ dB and $-135.0$ dB. Therefore, LRS extracts and highlights the sideband component by reducing the amplitudes of the linear and harmonic responses. The undesired linear response component is removed using SD in Fig. 4(e) and (f).

Fig. 2. Dog-bone aluminum specimen: (a) the geometry and dimensions of the specimen and (b) a close-up of the fatigue crack.

Fig. 3. Schematic diagram of the experimental setup.

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Note that SD also shifts the first spectral sideband component to near the DC value rather than near the probing frequency. 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).

3.3. Construction of the first sideband spectrogram (FSS)

The first spectral sideband presented in the previous experiment is generated only when the two conditions described in Section 2.1 are satisfied by careful selection of the probing and pumping frequencies. For guided waves, although the magnitude of the first spectral sideband is smaller than bulk waves, finding proper frequency combinations that satisfy these conditions is relatively easy due to the dispersive and multimode characteristics of the guided waves. Furthermore, the generation of the first spectral sideband heavily depends on the dynamic characteristics of the host structure, which constantly changes during the normal operation of the structure due to varying environmental and operational conditions such as temperature and loading.

For online monitoring of structures in operation, it is, therefore, advantageous to examine multiple frequency combinations of the two primary signals. In this study, FSS, which shows the amplitudes of the first spectral sideband component over a wide range of pumping and probing frequencies, is constructed as follows: First, the amplitudes of the first spectral sideband component corresponding to a specific pumping frequency and a certain frequency range of the linear chirp probing signal are computed using the previously described LRS-SD technique. Then, the previous step is repeated multiple times with a new pumping frequency. The pumping frequency is stepped from an initial to final value in fixed increments. Finally, the FSS map corresponding to all prescribed frequency values of the pumping and linear chirp probing signals is obtained.
Fig. 5 shows the FSS of SEN 1 and SEN 2 obtained by stepping the pumping frequency from 10 to 20 kHz with a 500 Hz increment and using a linear chirp probing signal spanning from 80 to 110 kHz. The fatigue damage is successfully detected from the FSS of both SEN 1 and SEN 2. It is clearly demonstrated that (1) the magnitudes of the first spectral sideband component obtained from the fatigued specimen in Fig. 5(b) and (d) are much larger than those from the intact specimen as shown in Figs. 5(a) and (c), and (2) the magnitudes of the first spectral sideband highly depend on both pumping and probing frequencies. In Fig. 6, similar trends were observed at higher frequency bands (pumping at 50–150 kHz with 5 kHz increment and probing at 400–500 kHz).

4. Crack detection in an aircraft fitting-lug

4.1. Experimental setup

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. 7. A 40-mm-long fatigue crack was introduced to one of the specimens by applying cyclic loading with varying amplitudes of 0–6.7 kN. This loading is equivalent to real operational loading corresponding to 1000 flight hours according to current aircraft design specifications.

A variable-amplitude cyclic loading spectrum was designed for application to the fitting-lug. The method used for generating the spectrum is representative of that used in aircraft design. However, all of the numbers and relationships are arbitrary, and do not represent any specific aircraft. The methods used to generate the loading are significant simplifications relative to typical practice.

The method begins by defining a set of mission types and assigning critical loading events for each mission. The three mission types used here are labeled “ferry”, “training” and “combat”. Assuming the loads for the fitting-lug depend only on the vertical acceleration at the center of gravity ($N_z$) of the aircraft, the loading of the fitting-lug can be specified by a sequence of maximum and vertical accelerations. In this work, an arbitrary set of seven maximum and minimum loading events are assigned for each mission type. Then, to create a sequence of load values, a sequence of flights is defined containing 3 ferry events, 17 training flights and 16 combat flights. This sequence of flights is assumed to be representative over the life of the system. The loading applied to the fitting-lug was generated using the preceding assumptions and the following steps:

- Generate a sequence of $N_z$ values selected from the assumed critical event sequence and assumed flight sequence.
- Add a 10 percent random value to each point in the sequence to represent the effects of parameters other than $N_z$ on the loading.

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Scale the $N_z$ values by 200 to convert from acceleration to load. The conversion factor from aircraft loading to part loads would typically be developed from stress analysis. In this case the conversion factor of 200 has been selected to obtain stresses in the desired range at the critical location on the fitting-lug.

For convenience, truncate the loads values to a convenient number of cycles; this work uses a load spectrum of 250 cycles.

The resulting load spectrum is shown in Fig. 8. During testing, blocks of loading using the data in Fig. 8 were applied at the tip of the beam to generate stress in the clevis. The spectrum was typically repeated four times to create 1000 cycles between inspections.

The average flight duration and percentages of flight types were chosen such that 10 of the loading blocks in Fig. 8 (i.e. 2500 cycles) correspond to 1000 “simulated flight hours”. Assuming 8000 h to be a typical fighter lifetime, then one lifetime is 20,000 cycles for this part.

Based on finite-element analysis of the specimen, high stress concentration is expected around the region, where the fatigue crack is introduced, during the real operational condition of an aircraft. Note that the majority of the previous nonlinear ultrasonic studies are performed on simple geometries such as beam, bar and plate-like structures, and there are few conducted on complex and bulky structures like the one presented in this experiment.

Similar to the dog-bone specimen, three identical dual PZTs manufactured by Metis Design were installed to each fitting-lug specimen using epoxy near the crack prone location as shown in Fig. 7. Here, 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 [27–28]. 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). Unlike the previous experiment, a single dual PZT was used for exerting both pumping and probing inputs. A sinusoidal pumping signal was applied to the outer ring and a linear chirp signal to the inner circle segment of ACT, respectively. Corresponding ultrasonic responses were measured using the inner circle parts of SEN 1 and SEN 2. Note that a larger PZT size is preferred for excitation while a smaller size is more advantageous for sensing [28].

The rest of the test setup was identical to the previous experiment.

4.2. Experimental results

Figs. 9 and 10 show the FSS obtained from the fitting-lug specimens with different pumping and probing frequency values. Similar to the FSS obtained from the dog-bone specimens, larger magnitudes of the first spectral sideband were
observed from the damaged case than from the intact case, and the modulation magnitude depends to a great extent on the pumping and probing frequencies. As the frequency value of the FSS goes up to a high-frequency region, the modulation occurs at fewer combinations of the probing and pumping frequencies as shown in Fig. 10. It is speculated that the synchronism and non-zero power flux conditions, which are necessary for the appearance of the spectral sideband components, are rarely satisfied at higher frequency values because the ultrasonic waves propagating through the thick specimens converge to non-dispersive surface Rayleigh waves. Note that, however, the magnitudes of the spectral sideband components at higher-frequency values are much larger than that at lower-frequency values where dispersive and multimode guided waves are dominant.

5. Conclusions

In this study, a fatigue crack detection technique using nonlinear ultrasonic wave modulation is developed. Permanently installed lead zirconate titanate (PZT) transducers are used for the generation of low-frequency pumping and high-frequency
Fig. 9. The FSS obtained from the fitting-lug specimens with pumping at 10–20 kHz and probing at 80–110 kHz: (a) and (b) are measured from the intact and damaged cases at SEN 1, respectively; (c) and (d) are measured from the intact and damaged cases at SEN 2, respectively.

Fig. 10. The FSS obtained from the fitting-lug specimens with pumping at 50–150 kHz and probing at 400–500 kHz: (a) and (b) are measured from the intact and damaged cases at SEN 1, respectively; (c) and (d) are measured from the intact and damaged cases at SEN 2, respectively.
probing inputs at two distinctive driving frequencies with a potential for continuous monitoring. The presence of a nonlinear mechanism such as a fatigue crack causes mixing of the linear responses and produces nonlinear modulation. In particular, the first spectral sideband, which is the nonlinear modulation component around the probing frequency, is isolated and explored in this study for fatigue crack detection. A signal processing technique combining linear response subtraction (LRS) and synchronous demodulation (SD) is developed to extract only the first sideband component from the measured ultrasonic time signal. First, the linear response components as well as harmonics are removed from the measured response using the proposed linear response subtraction (LRS) technique. Then, the first sideband component is isolated from the remaining modulation components using a combination of synchronous demodulation (SD) and band-pass filtering. The uniqueness of this study includes (1) use of low-amplitude ultrasonic inputs (less than $\pm$ 10 V and higher than 10 kHz) for both pumping and probing inputs, (2) development of a sideband extraction technique combining LRS and SD, (3) construction of FSS to identify the best combinations of the pumping and probing frequencies, (4) detection of an actual fatigue crack in a complex and bulky structure, and (5) generation of both pumping and probing inputs using a single dual PZT. Actual fatigue cracks grown in a metallic plate and a complex fitting-lug structure are successfully detected using the proposed technique even when the fatigue cracks are barely visible. In addition, the effect of the pumping and probing frequencies on the first spectral sideband amplitude is investigated using the first sideband spectrogram (FSS) obtained by sweeping both pumping and probing signals over specified frequency values. It has been demonstrated that the modulation is produced only with proper combinations of the pumping and probing frequencies.

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