

662. Nonlinear ultrasonic test using PZT transducer for crack detection in metallic component

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Abstract. A crack detection technique based on nonlinear ultrasonic is developed in this study. Acoustic waves at a chosen frequency are generated using an actuating lead zirconate titanate (PZT) transducer, and they travel through the target structure before being received by a sensing PZT wafer. Unlike an undamaged medium, a cracked medium exhibits high acoustic nonlinearity, which is manifested as harmonics in the power spectrum of the received signal. Experimental results also indicate that the harmonic components increase nonlinearly in magnitude with increasing amplitude of the input signal. The proposed technique identifies the presence of cracks by looking at the two aforementioned features: harmonics and their nonlinear relationship to the input amplitude. The effectiveness of the technique has been tested on aluminum specimens.

Keywords: nonlinear ultrasonic, fatigue crack, metallic component, crack detection.

1. Introduction

Metallic structures are largely found in mechanical, aerospace and civil infrastructures. Structural failures in metals are often attributed to cracks developed due to fatigue or fracture. Such cracks can develop at the flange-web junction of a beam, in the wings of an aircraft, in railway tracks or in the sub-structures of a power generation plant. In many cases, cracks cannot be avoided. Hence, there is a need for non-destructive inspection of such structural components.

Some of the popular NDT techniques for crack detection are acoustic emission [1], eddy currents [2], vibration-based techniques [3], impedance-based methods [4] and ultrasonic testing [5-7]. Ultrasonic testing using guided waves has recently gained popularity in those monitoring applications that can benefit from built-in transduction, moderately large inspection ranges, and high sensitivity to small flaws. Guided wave based methods can be broadly classified in two groups: (1) those based on the principles of linear acoustics like transmission, reflection, scattering, mode-conversion and absorption of acoustic energy caused by a defect [8-9]; and (2) those based on the principles of nonlinear acoustics like harmonics generation [10-12], frequency mixing [13, 14] and modulation of ultrasound by low frequency vibration [15-17]. Linear NDT techniques identify cracks by detecting the amplitude and phase change of the response signal caused by defects when a consistent probe signal is applied. On the other hand, nonlinear techniques correlate defects with the presence of additional frequency components in the output signal.

Many existing techniques suffer from one or more drawbacks: use of bulky equipment, unsuitability of automation and requirement of interpretation of data or image by trained engineers. These shortcomings make those methods less attractive for online continuous monitoring. The uniqueness of the present study lies in the authors' effort to overcome the aforementioned drawbacks by developing a crack detection technique using PZT wafers (which can be easily surface-mounted or embedded in the structure) and suggesting a damage detection process that can be readily automated. These features might make the proposed technique more suitable for online continuous monitoring of structures. Another unique aspect of this paper is to study the behavior of the nonlinear features with a propagating crack in metallic component.

The paper is organized as follows. First, the theoretical development for acoustic nonlinearity due to cracks is provided. Then, experimental studies performed to verify the effectiveness of the proposed technique are discussed. Finally, this paper concludes with a brief summary.

2. Theoretical backgrounds behind harmonics generation due to crack formation

It is well known that a crack in a structure causes nonlinear wave interaction leading to production of harmonics [10-17]. Although several theories were proposed to explain this phenomenon, a consensus regarding the physical understanding of the mechanism has not yet been reached. A summary of the existing theoretical models has been given by Parsons and Staszewski [17]. One of the popular theories is the “breathing crack model”, where the crack closes during compression and opens during tension when ultrasonic waves propagate through it.

Fatigue in metallic materials is a progressive, localized, and permanent structural damage that occurs when a material is subjected to cyclic or fluctuating stresses that are less than (often much less than) the static yield strength of the material [18]. The process initiates a discontinuity and becomes a microscopic crack. The crack propagates as a result of subsequent stress applications caused by cyclic loading. The fatigue life depends on the applied stress range and also on the structural geometry. A higher stress range leads to shorter fatigue life. A fracture is a local separation in a previously intact material body resulting from a stress application that is more than the material strength of the body [19]. Both fatigue and fracture cracks cause reduction of strength in a structural member which can eventually result in failure of the structure.

The opening and closing of a crack due to an incident ultrasonic wave can be regarded as a problem of interaction of ultrasonic waves with an interface of two rough surfaces in contact. A theoretical explanation of transmission and reflection of the second harmonic of a longitudinal wave at normal incidence has been given by Pecorari [20]. Pecorari also shows a nonlinear relationship between the amplitude of the second harmonic and the exciting amplitude of the incident wave; a part of this work is summarized as follows.

Using Greenwood and Williamson’s model [21] and Hertz’s law of contact between two elastic spheres, the normal pressure, P , is associated with the relative approach, δ , between the mean planes of the contacting surfaces by the following relationship [21, 22]:

$$P = \frac{2nER^2}{3(1-\nu^2)} \int_0^\delta (\delta - z)^{\frac{3}{2}} \varphi(z; N) dz \quad (1)$$

In Equation (1), n is the number of contacts per unit area; E and ν are the Young’s modulus and the Poisson’s ratio of the material, respectively; R is the radius of curvature of the asperities; φ is the height distribution of the asperities; z is the height of an asperity in transformed (linear) coordinates; and N is the “number of degrees of freedom” for the distribution φ . From Equation (1), Baltazar *et al.* [23] derived the normal interface stiffness, K_N and its derivative with respect to δ , $K_{N,1}$:

$$K_N = \frac{\partial P}{\partial \delta} = \frac{nER^2}{(1-\nu^2)} \int_0^\delta (\delta - z)^{\frac{1}{2}} \varphi(z; N) dz \quad (2a)$$

$$K_{N,1} = \frac{\partial K_N}{\partial \delta} = \frac{nER^2}{2(1-\nu^2)} \int_0^\delta (\delta - z)^{-\frac{1}{2}} \varphi(z; N) dz \quad (2b)$$

Now, let $u_m(x,t) = A_m \exp[j(\omega t - k_L x)]$ be a longitudinal wave incident on the crack-interface ($x = 0$) where t is time; ω is the angular frequency; $k_L = \omega / C_L$ is the wave number and C_L is the velocity of the longitudinal wave. Let u^- and u^+ be the total displacement fields towards the left ($x < 0$) and the right ($x > 0$) of the crack, respectively. The presence of a crack at $x=0$ gives rise to a set of nonlinear boundary conditions [20]:

$$\frac{\partial U^+}{\partial X} = \frac{\bar{K}_N}{\kappa^2} (\Delta U - \varepsilon A_m \Delta U^2) \quad (3a)$$

$$\frac{\partial U^+}{\partial X} = \frac{\partial U^-}{\partial X} \quad (3b)$$

In Equation (3), $U^{+,-} = u^{+,-} / A_m$; $\Delta U = U^+ - U^-$; $\kappa = C_L / C_T$ where C_T is the velocity of the shear wave; $X = k_T x$ where $k_T = \omega / C_T$ is the shear wave number; $\bar{K}_N = K_N / Z_T \omega$ where Z_T is the shear acoustic impedance of the medium and finally $\varepsilon = K_{N,1} / K_N$ is a small parameter representing the variation of the longitudinal interfacial stiffness caused by unit variation of the relative approach. The above boundary value problem was solved using a perturbation approach that exploits the harmonic balance method. The amplitudes of the first harmonic and second harmonic in the transmitted wave are given by [20]:

$$|A(\omega)| = \frac{1}{\sqrt{1 + \left[\frac{2\bar{K}_N}{\kappa} \right]^2}} A_m \quad (4a)$$

$$|A(2\omega)| = \frac{\varepsilon \bar{K}_N}{\kappa \sqrt{1 + \left[\frac{\bar{K}_N}{\kappa} \right]^2} \left[1 + \left[\frac{\bar{K}_N}{\kappa} \right]^2 \right]} A_m^2 \quad (4b)$$

The above results are valid up to the third order in the small parameter ε . Note that the amplitude of the second harmonic is nonlinearly related to the exciting amplitude and is also proportional to the parameter ε . Since the parameter ε is small, the amplitude of the second harmonic is expected to be smaller in comparison to that of the first harmonic. The third and higher harmonics can be shown to be present in the transmitted wave if higher order terms in ε are considered. The amplitudes of the higher harmonics are proportional to the second and higher powers of ε and much smaller in comparison to that of the second harmonic.

The proposed technique identifies the presence of cracks in a structure by looking at the harmonics of the exciting frequency in the output signal and their nonlinear relationship to the input amplitude [24, 25]. The amplitudes corresponding to the harmonics can be computed automatically using a Fast Fourier Transform (FFT). It is worth mentioning here that harmonics of the driving frequency are expected to be present even in the output signal from an undamaged specimen because of unknown sources of nonlinearity; e. g. nonlinearity in the attached circuit. Therefore, it will be a challenging task to distinguish between nonlinearity produced by a crack and nonlinearity produced by other sources. However, from experimental results it appears that the amplitude of the harmonics due to unknown sources of nonlinearity and the degree of their variation with the excitation voltage are much smaller compared to those due to crack-induced nonlinearity. Therefore, it is assumed in this study that nonlinearity is mainly attributed to crack

formation. To detect cracks, results obtained from a cracked specimen must be compared with baseline results from the pristine condition of the same specimen. Larger amplitudes of harmonics and greater variation thereof with excitation voltage indicate crack(s) in the structure.

3. Experimental results

The effectiveness of the proposed technique has been tested on an aluminum specimen. The results are detailed in the following sections. To ensure that crack opening and closing happens at the fullest extent, the exciting frequency was always chosen to be the same as the resonant frequency of the transducer-structure system.

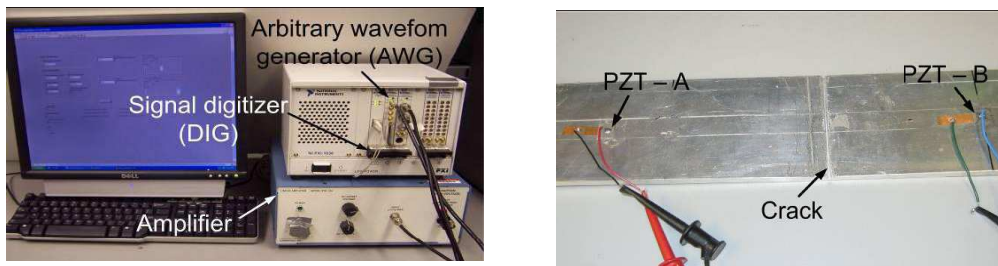


Fig. 1. Experimental setup for detecting cracks on aluminum beam: (a) Data acquisition system and the undamaged beam (b) Part of the beam showing the crack and the PZT transducers

The data acquisition system was composed of an arbitrary waveform generator (AWG), a high-speed signal digitizer (DIG), and a linear amplifier. The gain of the amplifier was set to two. Using the 16-bit AWG, a Gaussian white noise signal with a ± 10 peak-to-peak voltage was generated and applied to one of the transducers (PZT-A in Figure 1). PZT-A generated elastic waves and the response was measured at PZT-B. When the waves arrived at PZT-B, the voltage output from PZT-B was measured by the DIG. The sampling rate and resolution of the DIG were 10 MHz and 14 bits, respectively. Thereafter, FFT of the response measured at PZT-B was done and the resonant frequency of the transducer structure system was identified from the power spectrum. In order to improve the signal-to-noise ratio, the forwarding signals were measured thirty times and averaged in the frequency domain.

Figure 2 shows the amplitude spectrum of the output signal for the transducer-structure system when Gaussian white noise input was applied to the actuator. It can be observed from Figure 2 that the resonant frequency of the cracked system did not vary significantly from the resonant frequency of the undamaged system. The driving frequency for all subsequent experiments for all undamaged, notched and cracked states of the beam was therefore chosen to be 250 kHz.

Once the resonant frequency of the system was identified, a sinusoidal signal with a ± 1 peak-to-peak voltage and driving frequency equal to the resonant frequency of the system was generated using the same AWG and applied to PZT-A. FFT of the response measured at PZT-B was taken, and the absolute values of the FFT at the second and third harmonics of the driving frequency were noted. Again, the forwarding signals were measured twenty times and averaged in the frequency domain. The above procedure was then repeated with the peak-to-peak excitation voltage varying from $\pm 2V$ to $\pm 10V$ with an incremental step of $\pm 1V$. The same experiment was repeated three times for each state of the specimen (i.e. undamaged, notched and cracked) to see experiment to experiment variation.

Figure 3 indicates that the first harmonic amplitude of the output signal varies more or less linearly with the excitation voltage in the undamaged and notched cases as opposed to exhibiting nonlinear variance in the cracked case. This is an indication of nonlinearity due to crack, and the

crack caused the energy corresponding to the driving frequency to be shifted among the higher harmonics. Additionally, the amplitude of the first harmonic is much lower in the cracked beam compared to its undamaged and notched counterparts. The above phenomenon can be attributed to reflection and scattering of acoustic waves from the crack interface. In addition, for the crack case, the amplitude of the first harmonic varies nonlinearly with increasing input voltage.

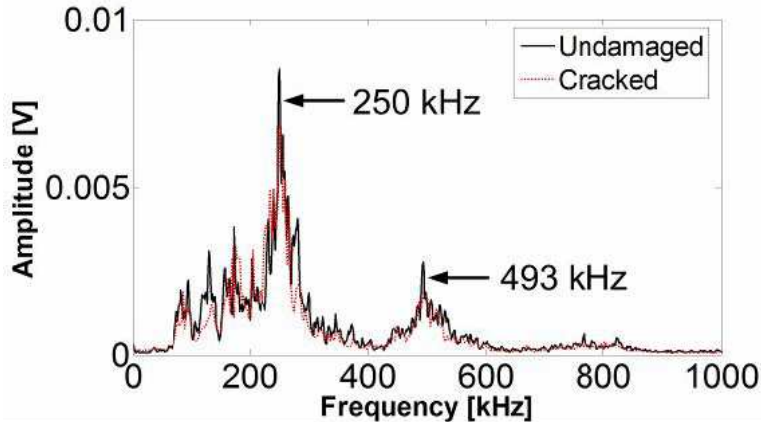


Fig. 2. Amplitude spectrum of the output signal for Gaussian white noise input at 20 V to the aluminum specimen

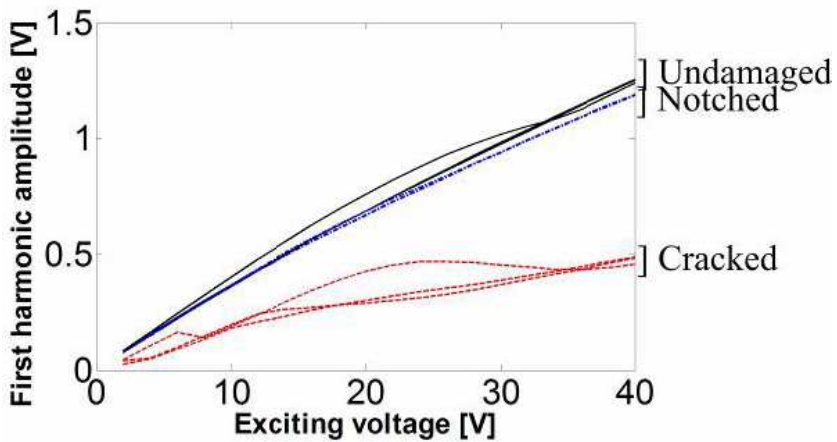


Fig. 3. Variation of the first harmonic (250 kHz) amplitude in the output signal with excitation voltage – results from three tests on the same aluminum specimen

It can be observed from Figure 4 that beyond a certain value of the exciting voltage, the second and third harmonic contents of the output signal are much more prominent in the cracked case than in the undamaged or notched cases. As predicted in Section 2, the amplitude of the second harmonic is significantly greater than the amplitude of the third harmonic. The observed nonlinear variation of the harmonic amplitudes with an increasing level of excitation is also consistent with the theory. This variation of the higher harmonic amplitudes with the excitation voltage is much more prominent in the cracked state than the variation in undamaged or notched states of the beam. The presence of harmonics in the undamaged and notched states can be attributed to unknown sources of nonlinearity such as circuit-nonlinearity. The repeatability of the results shown in Figures 3 and 4 are acceptable in so far as the undamaged, notched and cracked states of the beam can be easily classified.

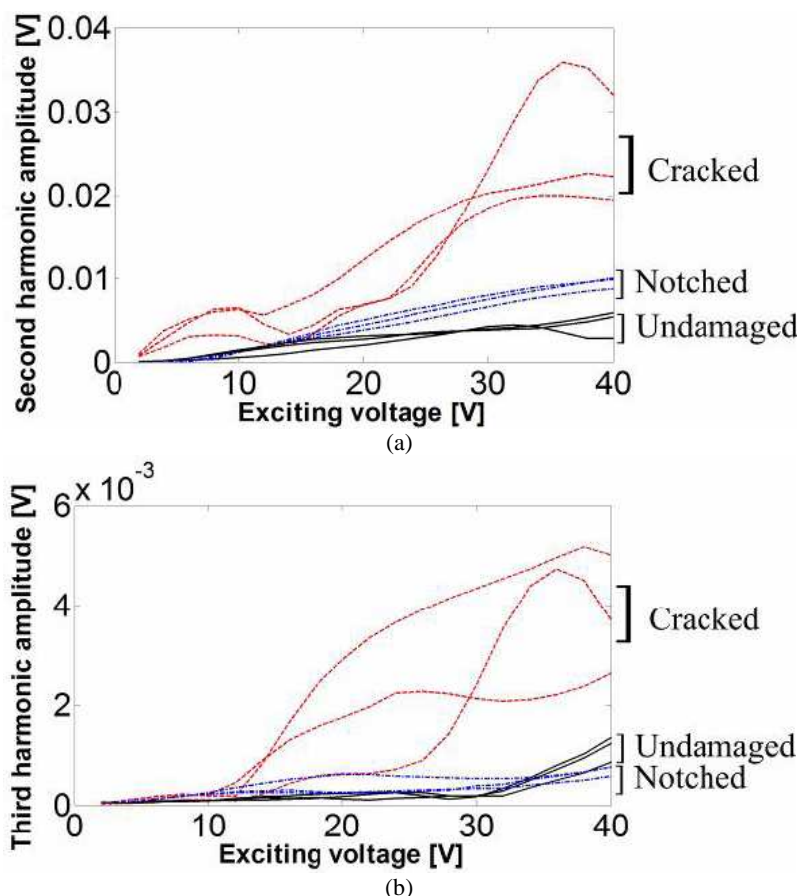


Fig. 4. Variation of (a) second harmonic (500 kHz) and (b) third harmonic (750 kHz) amplitudes in the output signal with the increasing excitation voltage – results from three tests on the same aluminum specimen

In conclusion, it can be said that the cracked state of the aluminum beam could be distinguished from its undamaged and notched states by considering the amplitudes of the harmonic components and their variation with the excitation voltage.

4. Conclusions

The objective of this study was to propose an easily automated crack detection technique in metallic structures using PZT transducers. Preeminent harmonics in the response signal from cracked specimens were observed as the input power of the driving PZT-wafer increased. The harmonic amplitudes also exhibit nonlinear variation with the increasing excitation voltage in the cracked specimens. The proposed technique identifies the presence of cracks by looking at two features: harmonics and their nonlinear relationship to the input amplitude. Experimental results revealed the presence of the second and third order harmonics in the undamaged and notched states of a structure caused by unknown sources of nonlinearity. Further study is warranted to address the issue of distinguishing the nonlinearity due to cracks from nonlinearity due to unknown sources. Nevertheless, it is possible to identify cracks in a specimen by looking at the greater magnitude of the harmonics and higher amount of their variation with the excitation voltage as compared to those in the pristine state of the structure.

Acknowledgments

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