A thermal sensitivity-based approach for enhancing robustness of ultrasonic evaluation of material acoustic nonlinearity

Kai Wang[a], Zhongqing Su[*a,b], Shenfang Yuan[c]

[a]Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR; [b]The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen 518057, P.R. China; [c]State Key Lab of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R. China

ABSTRACT

Despite demonstrated effectiveness in characterizing material properties or defect, the evaluation of material acoustic nonlinearity is highly prone to measurement contaminations introduced by various practical factors and the low robustness restricts its application. In order to obtain a precise quantification of the material acoustic nonlinearity in a robust manner, an approach based on the thermal fluctuations in nonlinear features of ultrasonic waves is developed. In this approach, the influence of temperature and defect on the interatomic distance is scrutinized analytically, and on this basis, the nonlinear features of ultrasonic waves linked with the temperature and defect is ascertained explicitly, whereby a thermal sensitivity index is proposed. With this thermal sensitivity index, the material acoustic nonlinearity can be evaluated without being affected by contaminations from practical sources, and therefore the defect which intensifies the material acoustic nonlinearity can be identified in a robust manner. Experimental validation corroborates the theoretical prediction, demonstrating that the proposed thermal sensitivity-based approach is capable of enhancing the robustness of material acoustic nonlinearity evaluation and defect characterization.

Keywords: material acoustic nonlinearity, thermal sensitivity, defect characterization, robustness enhancement

1. INTRODUCTION

The acoustic nonlinearity has been a core of research in recent years due to its superior sensitivity to material microstructure, defects and conditions. Numerous investigations have been reported to interpret the physical mechanisms behind the generation of acoustic nonlinearity, and the influence of material status on the acoustic nonlinearity have been well interrogated[1-3]. On this basis, a number of non-destructive evaluation (NDE) and structural health monitoring (SHM) methods, by making use of the acoustic nonlinearity, have been developed to inspect structures and to identify the present defects[4-7] which can be induced by inappropriate manufacturing, processing and various loading. Despite the maturity of these methods in laboratory environment, few of these methods have been implemented in the practical use, particularly for the SHM.

The gap between this modality and its practical application arises from the low robustness in ascertaining the precise measurement of acoustic nonlinearity under the practical conditions. It has been theoretically derived and experimentally evidenced that the acoustic nonlinearity is weak by nature for a diversity of material, and this leads to the fact that the measured nonlinear features in guided ultrasonic waves (GUWs) are usually at such a low level that they are susceptible to the contaminations from noises introduced in the process of real world application. It is well known that various factors, such as the noise from the operation environment, measuring systems, instruments, etc., impose significant effect on the measurement of acoustic nonlinearity, and even with the utilization of specially-designed instruments and complex signal processing approaches, introduction of nonlinearity to captured GUWs from undesirable sources is almost inevitable and uncontrollable. Exemplary, the coupling between the inspected structure and the Lead zirconate titanate (PZT) transducers, which are widely applied for SHM, is prone to degradation and aging during service time, introducing changes in the nonlinear features in the measured GUWs even without presence of defect, and this might lead to erroneous evaluation of the health status of inspected structures, causing the false alarm and eroding the confidence in the monitoring results.

[*] Zhongqing.Su@polyu.edu.hk; phone: +852-2766-7818; fax: +852-2365-4703

In this backdrop, numerous attempts[8-10] have been performed exhaustively to compensate the adverse influence from practical factors, and these attempts have made contributions to enhancing the precision of measurement, yielding results which exhibit satisfying repeatability albeit at a qualitative level. Nevertheless, none of these attempts is a generic approach capable of systematically and effectively eliminating the adverse influence from practical factors, and thus the measured acoustic nonlinearity displays unsatisfying repeatability at a quantitative level. This indicates that the robustness of acoustic nonlinearity-based SHM methods cannot meet the requirement of industrial practice, therefore precluding their application in real world.

With the recognition of this deficiency, we proposed a novel method, by making use of the thermal fluctuation in nonlinear features in GUWs, for the robustly precise evaluation of material acoustic nonlinearity. Utilizing the thermal fluctuations in nonlinear features in GUWs, methods for material evaluation have been reported. For example, the phase transition of some materials has been experimentally identified[11], and the interfacial stress between the matrix and reinforcements in composites was interrogated[12]. The analytical interpretation into the effect of temperature on the material property and nonlinear features in GUWs has been reported[13], attributing the generation of the nonlinearity to the “an-harmonicity” of the interatomic potential and explicitly depicting the dependence of nonlinear features in GUWs on temperature. However, few explicit techniques have been reported for the application of thermal fluctuation in nonlinear features in GUWs to the evaluation of material acoustic nonlinearity.

In the proposed approach, the material in inspected region is subjected to a known thermal variation, and the extent of thermal fluctuation in nonlinear features in GUWs depends on material physical properties. On this basis, by measuring the changes in nonlinear features in GUWs in the inspected regions, the acoustic nonlinearity of materials therein is interrogated, and the defect in materials, if any, can be identified and evaluated. During the ultrasonic evaluation process, the measuring systems and conditions are held constantly. In this context, the nonlinearity arising from other sources are invariant, and changes in nonlinear features in GUWs are solely associated with the thermal variation. Thus, the material acoustic nonlinearity is measured in an interference-free fashion.

2. THERMAL FLUCTUATIONS IN NONLINEAR ULTRASONIC WAVES

To understand the effect of thermal variation on the nonlinear features in ultrasonic waves, the physical mechanisms behind the generation of material acoustic nonlinearity is recalled. The material acoustic nonlinearity can largely be depicted using the nonlinear elastic moduli – a physical property usually denoted as third-order-elastic constants. The constants are physically linked with the interatomic bonding forces in materials, and the interatomic bonding forces are associated with the interatomic distance. These two parameters are governed by the interatomic potential which represents the potential energy of a system of atoms in a material and governs the deformation at the atomistic level. To delineate and approximate this interatomic potential, a few models have been developed, including the embedded atom model, Lennard-Jones potential, Sutton-Chen potential, glue potential, etc. The commonly used Lennard-Jones potential is employed in this study, which reads

$$E_{LJ}(r) = 4w\left[\left(\frac{q_{LJ}}{r}\right)^{12} - \left(\frac{q_{LJ}}{r}\right)^{6}\right]. \tag{1}$$

In the above, E_{LJ} is the interatomic potential as a function of interatomic distance r, as shown in Figure 1. w and q_{LJ} denote the empirical parameters accounting for the depth of the potential well and the distance between two atoms at which the potential is zero, respectively.

E_{LJ}.

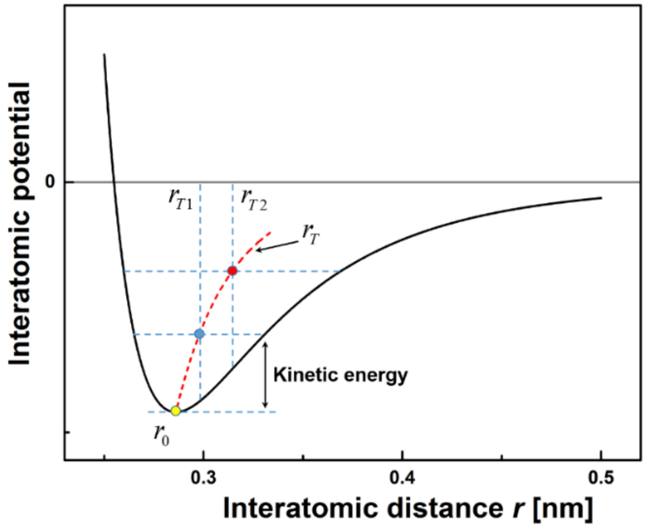


Figure 1. The interatomic potential as a function of the interatomic distance

When the temperature of the waveguide is elevated, the kinetic energy of atoms/molecules in the material is enlarged, and this leads to an increased interatomic potential, inducing a greater amplitude of atoms/molecules vibration. In this context, the average interatomic separation can be depicted using the midpoint between the repulsive and attractive branches of the potential, and since the potential is “an-harmonic”, as shown in Figure 1, the average interatomic separation experiences an increasing, manifesting a macroscopic thermal expansion. In the conventional linearized thermal expansion theory, the relation between the interatomic distance r and the temperature can be described as:

$$r(T) = r_0[1+\alpha(T-T_0)], \tag{2}$$

where α is the thermal expansion coefficient of a material, and $T-T_0$ is the temperature change from T_0 at which the initial interatomic distance is r_0.

On top of the temperature variation, presence of defect in material also leads to changes in interatomic distance. For example, in the waveguide which is subjected to repetitious loading, the fatigue damage can be developed, and in the fatigued region, dislocations are always generated, leading to changes in material microstructure and increasing in interatomic distance. This defect-induced interatomic distance increasing is denoted as r_{abn}. It is therefore that, taking both the temperature variation and r_{abn} into account, the total interatomic distance can be rewritten as

$$r_{tot}(T) = r_0 + \alpha(T-T_0) + r_{abn}. \tag{3}$$

With the interatomic distance in material with and without defect, as described in Eqs. (2) and (3), the interatomic bonding force (denoted as F) can be obtained analytically. On this basis, the propagation of the ultrasonic waves in a one-dimensional scenario can be derived using conventional equilibrium principle[1], as

$$\begin{gathered}\frac{\partial^2 u_1}{\partial t^2} = V_p[1-\gamma(\frac{\partial u_1}{\partial x_1})]\frac{\partial^2 u_1}{\partial {x_1}^2},\\ V_p = \sqrt{\frac{C(T, r_{abn})}{\rho}},\ \gamma = -\frac{D(T, r_{abn})}{C(T, r_{abn})},\end{gathered} \tag{4}$$

where u_1 is the atomic displacement in the direction of x_1. V_p and γ denote the propagation velocity and nonlinear parameter, respectively. $C(T, r_{abn}) = \partial^2 E/\partial r^2$ and $D(T, r_{abn}) = \partial^3 E/\partial r^3$ are obtained from the differentiations of the E_{LJ}.

Solving Eq. (4) using conventional perturbation method[1], the displacement field of ultrasonic waves which embraces the linear portion u_1^1 and the nonlinear portion u_1^2 can be attained. The commonly used nonlinear index β is employed as a quantitative evaluation of the acoustic nonlinearity, which reads

$$\beta(T, r_{abn}) = \frac{A_2(T, r_{abn})}{A_1(T, r_{abn})^2} \propto -\frac{D(T, r_{abn})}{C(T, r_{abn})}. \tag{5}$$

With Eq. (5), the relation between the nonlinear index and the temperature is explicitly obtained, and the trend of β against the interatomic distance r is displayed in Figure 2. As commented earlier, the measurement and evaluation of the β is susceptible to contaminations from various practical sources, making it difficult to measure the β precisely and robustly. Therefore, instead of quantifying the absolute value of β, the fluctuation that the β experiences in respond to a temperature variation is assessed here. To this end, an acoustic nonlinearity thermal sensitivity index TSI is defined as

$$TSI = \frac{\triangle\beta(T, r_{abn})}{\triangle t}, \tag{6}$$

where $\triangle\beta$ denotes the fluctuation in nonlinear features in GUWs when the material is subjected to a temperature variation $\triangle t$.

When measuring the defined TSI, all other conditions are held constant. In this context, the interference from various sources is invariant, and therefore the index TSI is only linked with the material status, i.e. the r_{abn}. From Figure 2, it is clearly observed that when undergoing a certain temperature elevation, the materials with defect exhibit a more remarkable increase in β than intact materials, thereby leading to a higher TSI.

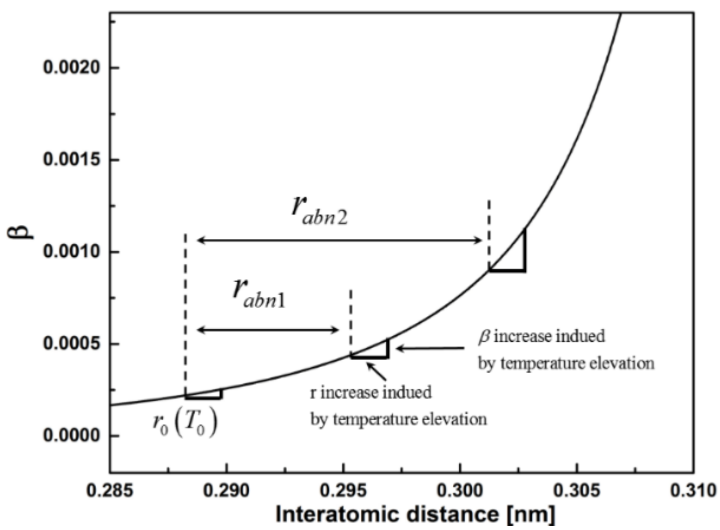


Figure 2. Correlation between the β and the interatomic distance

Inversely, the material status, which can be depicted using r_{abn}, can be evaluated using the thermal fluctuation. This provide the theoretical basis for the proposed approach which is capable of outstanding the material defect in a robust manner. The implementation of this method can be facilitated by active temperature control, on which basis, the proposed thermal fluctuation-based approach is immediately available to many NDE and SHM applications where nonlinear ultrasonic identifying, imaging and evaluating[14, 15] is currently utilized.

3. EXPERIMENTAL EVALUATION OF FATIGUE DAMAGE USING THERMAL FLUCTUATION

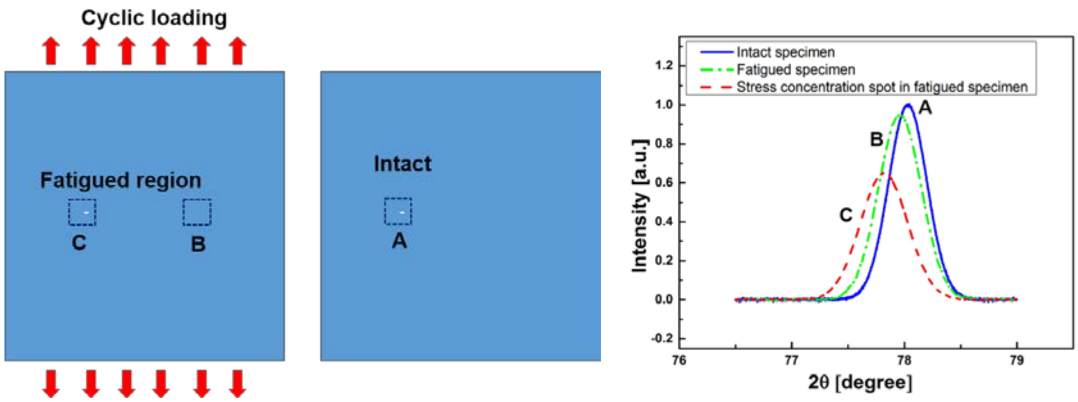
For proof-of-concept, the proposed approach is applied to evaluate the fatigue damage developed in aluminum (Al 6061) plates. A through-thickness slot is treated at the center of the waveguide using a fine drilling process, to serve as a crack precursor, from the tip of which the fatigue damage is produced under cyclic loads. Upon 120,000 cycles of a cyclic load (5~26 kN; ratio 0.19) applied to the waveguide at a frequency of 10 Hz via a fatigue test machine (GoPoint®, SDF2000), as shown in Figure 3(a), the waveguide is observed to bear a 1 mm hairline fatigue crack from the tip of the crack precursor, which indicates the development of fatigue damage with a small scale. The precise imaging and further quantitative evaluation of this damage represents an unsolved research problem of critical importance. In the fatigued region, a diversity of defects are induced, including dislocations, permanent slip band, micro cracks, etc., and these defects lead to the increasing in material nonlinearity, as investigated elsewhere[16]. On this basis, methods using the material-related nonlinear features in GUWs have been intensively studied. It is worth noting that the transducers mounted on the structure to monitor its health status are also influenced by the repetitious loading as mentioned in the above, and as a result, the coupling between the transducers and the structure might be degraded. This degradation can introduce additional nonlinearities into the captured GUW signals, which is not related with the fatigue damage.

The defects in the fatigued region damage usually lead to changes in the material microstructure, causing increasing in interatomic distance. To measure the interatomic distance in the intact waveguide and the fatigued waveguide, the Rigaku Smartlab system, as displayed in Figure 3(b), is used to perform the X-ray radiation diffraction (XRD) test on the specimen from the intact plate and the fatigued plate, respectively, as highlighted by the rectangle in Figure 4(a).

(a) (b)

Figure 3. (a) Fatigue test and (b) XRD test

From the XRD test, the diffraction pattern for the specimens are ascertained, as shown in Figure 4(b), with which the interatomic spacing can be attained. Compared with the pristine material in the intact specimen, the decreasing in the diffraction angle and the increasing in the width of the XRD pattern in the fatigued specimen are clearly exhibited, which, respectively, indicates that the load-induced intensification in interatomic distance and the increasing in density of dislocation and mirco-cracks. Both lead to the intensification of interatomic distance in the fatigued specimen.



(a) (b)

Figure 4. (a) Specimens from intact waveguide and fatigued waveguide; (b) (311) diffraction peaks in the XRD pattern

The PZT wafers are mounted on the surface of the waveguide to form a sensor network with the inspection region covering the fatigue damage, as displayed in Figure 5. A modular nonlinear ultrasonic system (RITEC® RAM-5000 SNAP system) is used to produce an excitation signal, and after filtering out the second harmonics, the excitation signal is applied on the PZT wafers to excite probing waves in the waveguide, as shown schematically in Figure 5. The inspected region is heated with heat flux (at the temperature of 360℃) in the first minute, and the temperature of the heated region is uniformly elevated. Upon the finishing of the heating, the specimens are naturally cooled down to the room temperature.

During the course of heating and cooling, the ultrasonic waves from each sensing path in the sensor network are consecutively captured and recorded, from which the nonlinear features, i.e. high order harmonics, are extracted using a Fourier transform processing technique. Figure 6 displays the amplitude of the second harmonics from three representative sensing paths, and three distinct characteristics are clearly observed: i) the amplitude of second harmonic is increased when heated, and after cooled down to the room temperature, it returns to the original level before heating; ii) the fatigue damage induces more remarkable increasing than intact material, and the returning of the amplitude of the second harmonic to the original level costs more time; and iii) the severer the fatigue damage, the greater increasing in the amplitude of second harmonic. During the entire course, the fundamental ultrasonic waves experience insidious changes. This phenomena well corroborates the theoretically interpreted temperature-dependency of nonlinear features in GUWs.

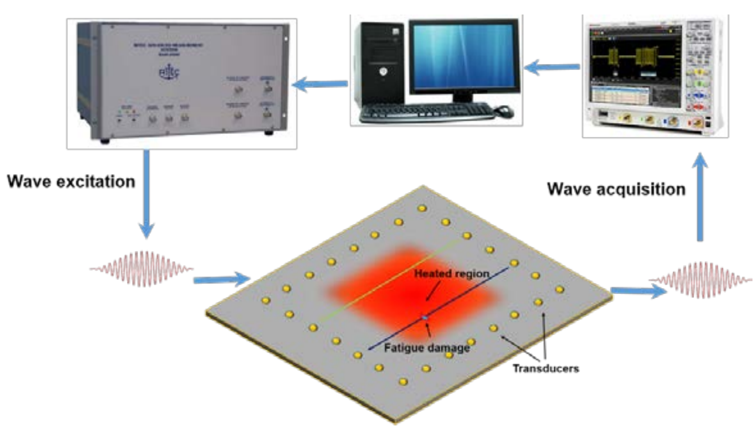


Figure 5. Ultrasonic test set-up

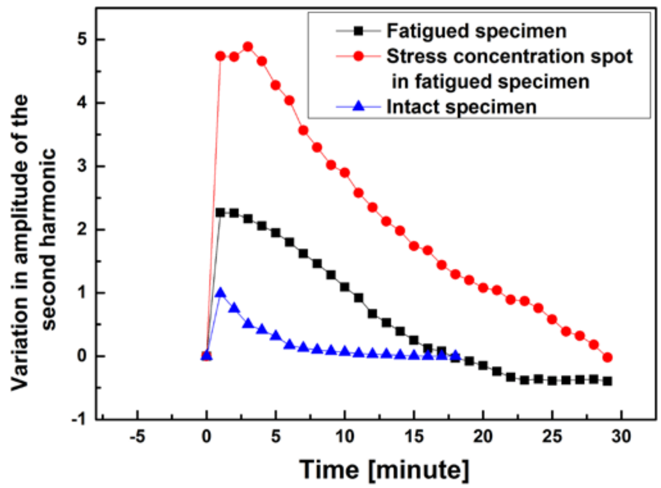


Figure 6. Amplitude of second harmonics in GUWs

With the ascertained thermal fluctuations, a diversity of imaging method, such as nonlinear phased array imaging[14] and path-based imaging[17], can be applied to identify and image the defect existing in the waveguide. In this study, the reconstruction algorithm probability imaging method[17] is used, in which wave signals from all sensing paths in the sensor network are synthesized, yielding a quantitative evaluation of the defect and intuitively displayed in a pixelated image, as shown in Figure 7(a). As a comparison, Figure 7(b) displays the imaging result using the absolute value of conventional β measured using the sensor network, and it is clearly demonstrated that the contamination is such remarkable that defect-induced intensification might be obfuscated or even overwhelmed. Therefore, the defect is not identified, and this claims the low robustness of existing NDE and SHM methods based on the utilization of β, eroding the confidence in the evaluation results of these methods. Consequently, defect might be overlooked or false alarm might be sent, and both are the critical concerns for industrial applications.

On the contrary, the proposed technique exhibits a highly precise evaluating and imaging results using the same set-up. The results presented in Figure 7(a) clearly demonstrate the capability of the proposed approach to enhance the robustness of existing acoustic nonlinearity-based NDE and SHM methods, and as an extra merit, this approach enables the potential to provide sensitivity to previously undetectable structural defects, since the ultrasonic evaluation of material acoustic nonlinearity can be performed in a precise manner.

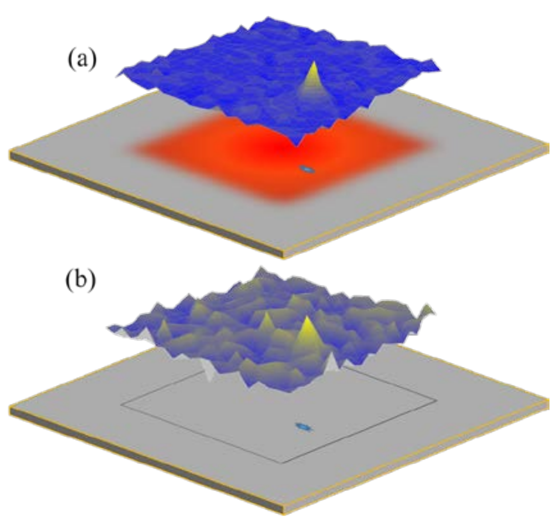


Figure 7. Imaging result using (a) the proposed TSI and (b) the absolute value of β

4. CONCLUSION AND DISCUSSIONS

In order to obtain a precise quantification of the material acoustic nonlinearity, preferably in a robust manner, an approach based on the thermal fluctuations in nonlinear features of ultrasonic waves is developed. In this approach, the temperature-dependency of the interatomic distance is scrutinized analytically, and on this basis, the nonlinear features of ultrasonic waves linked with the temperature and defect is ascertained explicitly, whereby a thermal sensitivity index is proposed. By utilizing the thermal sensitivity index, the material acoustic nonlinearity can be evaluated, and the defect which intensifies the material acoustic nonlinearity can be identified. Experimental validation corroborates the theoretical prediction, demonstrating that the proposed thermal fluctuation-based approach is capable of enhancing the robustness and precision of material acoustic nonlinearity quantification and defect characterization.

In the future research, the pulse electric current stimulation will be used to facilitate the proposed approach. When subjected to a pulse electric current, the current flows along the fatigue crack because of the electrical resistance on the crack's surface. Thus, a high density electric current field is formed at the crack tip, incurring intensive heat generation. The merits of the combination of the proposed approach and the current stimulation are twofold: i) this local heating can induce thermal stress in the vicinity of the crack, intensify the thermal sensitivity at the fatigued region significantly, therefore enhancing the sensitivity of the proposed approach; and ii) it is usually used as an aiming recovery method for material deterioration, since the stress concentration at the crack tip can be reduced and the growth of crack is stopped.

ACKNOWLEDGEMENT

The work was supported by a Key Project (No. 51635008) and a General Project (51875492) of the National Natural Science Foundation of China. The authors also acknowledge the support from the Hong Kong Research Grants Council via General Research Fund (Nos.: 15201416 and 15212417).

REFERENCES

[1.] W. De Lima and M. Hamilton, "Finite-amplitude waves in isotropic elastic plates". J. Sound Vib. 265, 819-839 (2003).
[2.] M. Deng and J. Pei, "Assessment of accumulated fatigue damage in solid plates using nonlinear Lamb wave approach". Appl. Phys. Lett. 90, 121902 (2007).
[3.] I. Y. Solodov, N. Krohn, and G. Busse, "CAN: an example of nonclassical acoustic nonlinearity in solids". Ultrasonics 40, 621-625 (2002).
[4.] A. J. Croxford, J. Cheng, and J. N. Potter, "Nonlinear phased array imaging", Health Monitoring of Structural and Biological Systems 2016,98052B (2016).
[5.] I. Solodov, J. Wackerl, K. Pfleiderer, and G. Busse, "Nonlinear self-modulation and subharmonic acoustic spectroscopyfor damage detection and location". Appl. Phys. Lett. 84, 5386-5388 (2004).
[6.] M. Hong, Z. Su, Y. Lu, H. Sohn, and X. Qing, "Locating fatigue damage using temporal signal features of nonlinear Lamb waves". Mech. Syst. Signal Process 60, 182-197 (2015).
[7.] K.-Y. Jhang, "Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review". Int. J. Precis. Eng. Manuf. 10, 123-135 (2009).
[8.] S. Haupert, G. Renaud, J. Riviere, M. Talmant, P. A. Johnson, and P. Laugier, "High-accuracy acoustic detection of nonclassical component of material nonlinearity". J. Acous. Soc. Am. 130, 2654-2661 (2011).
[9.] A. J. Croxford, J. Moll, P. D. Wilcox, and J. E. Michaels, "Efficient temperature compensation strategies for guided wave structural health monitoring". Ultrasonics 50, 517-528 (2010).
[10.] T. Clarke, P. Cawley, P. D. Wilcox, and A. J. Croxford, "Evaluation of the damage detection capability of a sparse-array guided-wave SHM system applied to a complex structure under varying thermal conditions". IEEE Trans. Ultrason. Ferroelectr. Freq. Control 56, (2009).
[11.] Y. Zhang, V. Tournat, O. Abraham, O. Durand, S. Letourneur, A. Le Duff, *et al.*, "Nonlinear mixing of ultrasonic coda waves with lower frequency-swept pump waves for a global detection of defects in multiple scattering media". J. Appl. Phys. 113, 064905 (2013).

[12.] H. Mohrbacher and K. Salama, "The Temperature Dependence of Third-Order Elastic Constants in Metal-Matrix Composites," in *Review of Progress in Quantitative Nondestructive Evaluation*, ed: Springer, 1993, pp. 2091-2097.
[13.] C. Nucera and F. L. di Scalea, "Nonlinear wave propagation in constrained solids subjected to thermal loads". J. Sound Vib. 333, 541-554 (2014).
[14.] J. Potter, A. Croxford, and P. Wilcox, "Nonlinear ultrasonic phased array imaging". Phys. Rev. Lett. 113, 144301 (2014).
[15.] C. Payan, T. Ulrich, P. Le Bas, M. Griffa, P. Schuetz, M. Remillieux, *et al.*, "Probing material nonlinearity at various depths by time reversal mirrors". Appl. Phys. Lett. 104, 144102 (2014).
[16.] R. E. Apfel and E. C. Everbach, "Application of the acoustic nonlinearity parameter to tissue composition prediction". J. Acous. Soc. Am. 84, S138-S138 (1988).
[17.] Q. Wang, M. Hong, and Z. Su, "An in-situ structural health diagnosis technique and its realization via a modularized system". IEEE Trans. Instrum. Meas. 64, 873-887 (2015).