Nonlinear electro-mechanical impedance spectroscopy for fatigue crack monitoring

Lu, Runye, Shen, Yanfeng

Runye Lu, Yanfeng Shen, "Nonlinear electro-mechanical impedance spectroscopy for fatigue crack monitoring," Proc. SPIE 12048, Health Monitoring of Structural and Biological Systems XVI, 120480W (19 April 2022); doi: 10.1117/12.2612590

Event: SPIE Smart Structures + Nondestructive Evaluation, 2022, Long Beach, California, United States

Nonlinear Electro-Mechanical Impedance Spectroscopy for Fatigue Crack Monitoring

Runye Lu[a], Yanfeng Shen*[a,b]

[a]University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, China, 200240; [b]Shanghai Key Laboratory for Digital Maintenance of Buildings and Infrastructure, Shanghai, China, 200240

ABSTRACT

This paper presents a Nonlinear Electro-Mechanical Impedance Spectroscopy (NEMIS) methodology for fatigue crack monitoring. Different from the conventional Electro-Mechanical Impedance Spectroscopy (EMIS) implemented in frequency domain, the current work employs a temporal chirp-based interrogative excitation to obtain the impedance spectrum, and simultaneously captures the Contact Acoustic Nonlinearity (CAN) arising from fatigue crack interfaces. To develop an insight into the mechanism behind the chirp-based impedance method, a comparative investigation between the conventional EMIS and the chirp-based NEMIS algorithm is conducted. Numerical studies are carried out on a transitional-bilinear CAN model to illustrate the chirp-induced higher harmonics and nonlinear mixed-frequency response features. Furthermore, finite element simulations are conducted to demonstrate the feasibility of the chirp-based NEMIS. Finally, experimental validation of the NEMIS method is performed. The chirp-based impedance spectra are verified against results from the impedance analyzer. Fatigue cracks are nucleated and grown on the MTS testing machine with cyclic loadings. Higher harmonics and wave modulation features can be successfully captured to manifest the existence of the fatigue crack. Quantification on the severity of the crack is conducted using the nonlinear damage index. The paper finishes with summary, concluding remarks, and suggestions for future work.

Keywords: electromechanical impedance, nonlinear ultrasonics, fatigue crack, wave modulation, higher harmonics, damage detection

1. INTRODUCTION

Electromechanical Impedance Spectroscopy (EMIS) has been widely investigated as an effective technique for the Structural Health Monitoring (SHM). It employs piezoelectric wafer active sensors (PWAS), coupling the mechanical impedance of the host structure with the electrical impedance measured at sensor's terminals. EMIS is sensitive to local damage types like cracks, notches, corrosions, and debondings [1-3] and has been put into wide applications on various kinds of structures [4, 5]. However, the linear ultrasonic features from the EMIS method are not sensitive enough to detect incipient damages [6], especially early stage fatigue cracks.

Fatigue cracks have been widely existing in a broad range of engineering structures. They usually initiate at an unperceivable level in a closed stage and grow to a critical level under long-term cyclic loadings, jeopardizing structural integrity and finally leading to catastrophic failures without warnings. Under such a background, ultrasonic guided wave techniques, among many structural health monitoring (SHM) and non-destructive testing (NDT) methods, have gained considerable popularity for their convenience and large sensing areas [7-9]. Most conventional ultrasonic techniques utilize linear feature modifications (like transmission, reflection, attenuation, mode conversion etc.) of ultrasonic waves at the damage sites [10-13]. However, these linear methods are only feasible when the fatigue cracks attain gross level and are not sensitive enough to detect the existence of incipient cracks [14, 15].

To break through the limitation of the linear methods, enormous endeavors have been devoted to the development of nonlinear vibro-acoustic techniques for fatigue crack detection at early stages. Several nonlinear features have shown prominence for SHM purpose, the most pivotal approaches among which can be categorized into three general groups. The first group focuses on the generation of nonlinear wave modulation, also named as vibro-acoustic modulation (VAM) [16]. Methods in this group employ low-frequency but high-magnitude sinusoidal signal as 'pumping signal' to modulate high-frequency ultrasonic signal.[17] Lim et.al proposed a reference-free fatigue crack detection strategy using nonlinear

Health Monitoring of Structural and Biological Systems XVI, edited by Paul Fromme,
Zhongqing Su, Proc. of SPIE Vol. 12048, 120480W · © 2022 SPIE
0277-786X · doi: 10.1117/12.2612590

ultrasonic modulation [18]. The spectral correlation was applied to isolate the nonlinear wave modulation components in noisy environments by Liu et.al [19]. It was initially considered that the closing and opening motions of the crack give rise to nonlinear modulation [20, 21]. However, Klepka et.al illustrated that the dislocation, local stress concentration, friction, and temperature gradient due to the existence of cracks will also generate nonlinear modulation despite at a low strain level and without crack opening and closing [22]. Sohn et.al concluded from the findings that (1) fatigue cracks can be detected before growing to an open crack and (2) the excitation amplitude is unnecessary to be extremely high to generate opening and closing of the cracks [23].The second group is based on sub-harmonic and higher harmonic generation. The ultrasonic waves, when propagating in the elastic structure, can be distorted by the nonlinearity of the medium, leading to the frequency shifting from the excitation frequency to higher-order harmonic frequencies [15]. In particular, the 'breathing' motion (opening and closing) of the crack interface introduces additionally much stronger nonlinearity, also called contacting acoustic nonlinearity (CAN), which usually includes sub-harmonic and higher harmonics [24]. Zhang et.al proposed the application of sub-harmonic resonance for the detection of bolt looseness [25]. The subharmonic acoustic spectroscopy for damage detection and location was also presented by Solodov et.al [26]. Yang et.al exploited low frequency lamb waves to generate second harmonic for fatigue crack detection [27].The third group concentrates on the shift of resonance frequency. The existence of fatigue damage can result in a shift of the resonant frequency when ultrasonic waves travel through. Nonlinear resonant ultrasound spectroscopy (NRUS) was applied to detect the corrosion cracks in stainless steel rods by Hogg et.al [28]. Meo et.al also used nonlinear spectroscopy methods for detecting damage in composite materials [29]. Other nonlinear vibro-acoustic techniques have also been investigated by many researchers. The spectral correlation algorithm has been utilized to extract other nonlinear features for crack monitoring [30-33]. Dual frequency mixing [34] and time reversal [35, 36] techniques also showed good performances. All these cases demonstrate that nonlinear ultrasonic technique is a good candidate for fatigue crack detection and monitoring.

In addition to the techniques exploiting nonlinear features for crack detection, tremendous efforts have also been paid to the nonlinear modeling and numerical simulation. An analytical model considering the rough crack interface features was adopted to investigate the nonlinear resonance mechanism [37]. A novel concept of the nonlinear pseudo-force in a breathing crack was analytically formulated [38]. Various types of elastic and dissipative models of nonlinear wave-crack interaction was presented by Broda et al [39]. Local interaction simulation approach (LISA) was extended to simulate nonlinear wave damage interaction at fatigue cracks [40, 41]. In spite of the tremendous superiorities of these nonlinear ultrasonic techniques, it can be concluded that the majority of aforementioned methods possess the following deficiencies: (1) they employ two or more PWAS sensors (usually forming a pitch-catch mode), (2) they only focus on a single or limited nonlinear features, (3) linear and nonlinear features are separated, and (4) structural information obtained from the response signal is not abundant (lack of impedance information), (5) the nonlinearity is weak and thus its measurement is challenging [42].

Envisaging these limitations of the existing nonlinear ultrasonic techniques, this paper presents a multifunctional Nonlinear Electro-Mechanical Impedance Spectroscopy (NEMIS) to bridge the gap between the conventional EMIS and various nonlinear ultrasonic techniques. It is worth mentioning that some researchers from Electrical and Computer Engineering (ECE) and chemistry field once proposed other impedance measurement using chirp signal, which was different from EMIS [43-45]. This comprehensive method is distinctive from conventional EMIS and nonlinear techniques. Compared with the conventional EMIS, the proposed NEMIS method utilizes temporal chirp excitation to obtain the time-history transient dynamic information, rather than a stepwise sweeping excitation. Compared with the conventional nonlinear ultrasonic method, the proposed NEMIS method requires only a single PWAS transducer functioning as both actuator and receiver, rather at least two transducers for a pitch-catch setup. Thus, NEMIS combines the merits of conventional EMIS and nonlinear ultrasonics to from a new technique, which is time-saving and enables the attainment of both linear feature (shifting of impedance resonance peaks) and nonlinear features (higher harmonics and wave modulation) for fatigue crack detection. Furthermore, a new nonlinear index based on chaos and fractal theory is considered for the quantification of fatigue crack severity.

This paper is organized as below. It starts with the comparative illustration of the chirp-based impedance procedure compared with the traditional EMIS. Subsequently, a transitional-bilinear CAN model is applied to demonstrate the generation of higher harmonics, along with the chirp-induced nonlinear wave modulation. Furthermore, FEM simulations are conducted to prove the feasibility of the chirp-based impedance spectrum by comparing with the results from the harmonic analysis. Systematic experiments are conducted to verify the effectiveness of the NEMIS. The accuracy of the chirp-based impedance method is demonstrated against the impedance spectra obtained from the impedance analyzer on aluminum beam specimens. Fatigue cracks are generated on the MTS testing machine under cyclic loading. The expanded nonlinear impedance spectra are obtained for evaluating the severity of the fatigue cracks, using the proposed chaos-based nonlinear index.

2. THEORETICAL ILLUSTRATION OF NEMIS FOR FATIGUE CRACK MODELLING

2.1 Comparative illustration of EMIS and NEMIS

The conventional EMIS takes a frequency domain measurement using a stepwise sweeping excitation. In numerical simulations via the commercial FEM software, the electromechanical impedance can be obtained by the harmonic analysis using multi-physics finite elements. Harmonic analysis excites the system with a sinusoid signal at a certain frequency and captures the stable response, from which one can calculate a single impedance value. By repeating this procedure from a low frequency to high frequency, the impedance spectrum can be obtained by the steady-state response at each step. The entire procedure can be illustrated in Figure 1(a). In experimental implementation of conventional EMIS, the impedance analyzer is used to obtain the impedance spectra. The instrument is usually expensive and bulky, which is not feasible and portable for engineering measurement. Moreover, the frequency sweeping process in an impedance analyzer is time-consuming since it needs to capture the steady-state response for each frequency step. All of these bring about the inconvenience and limitations on the conventional EMIS.

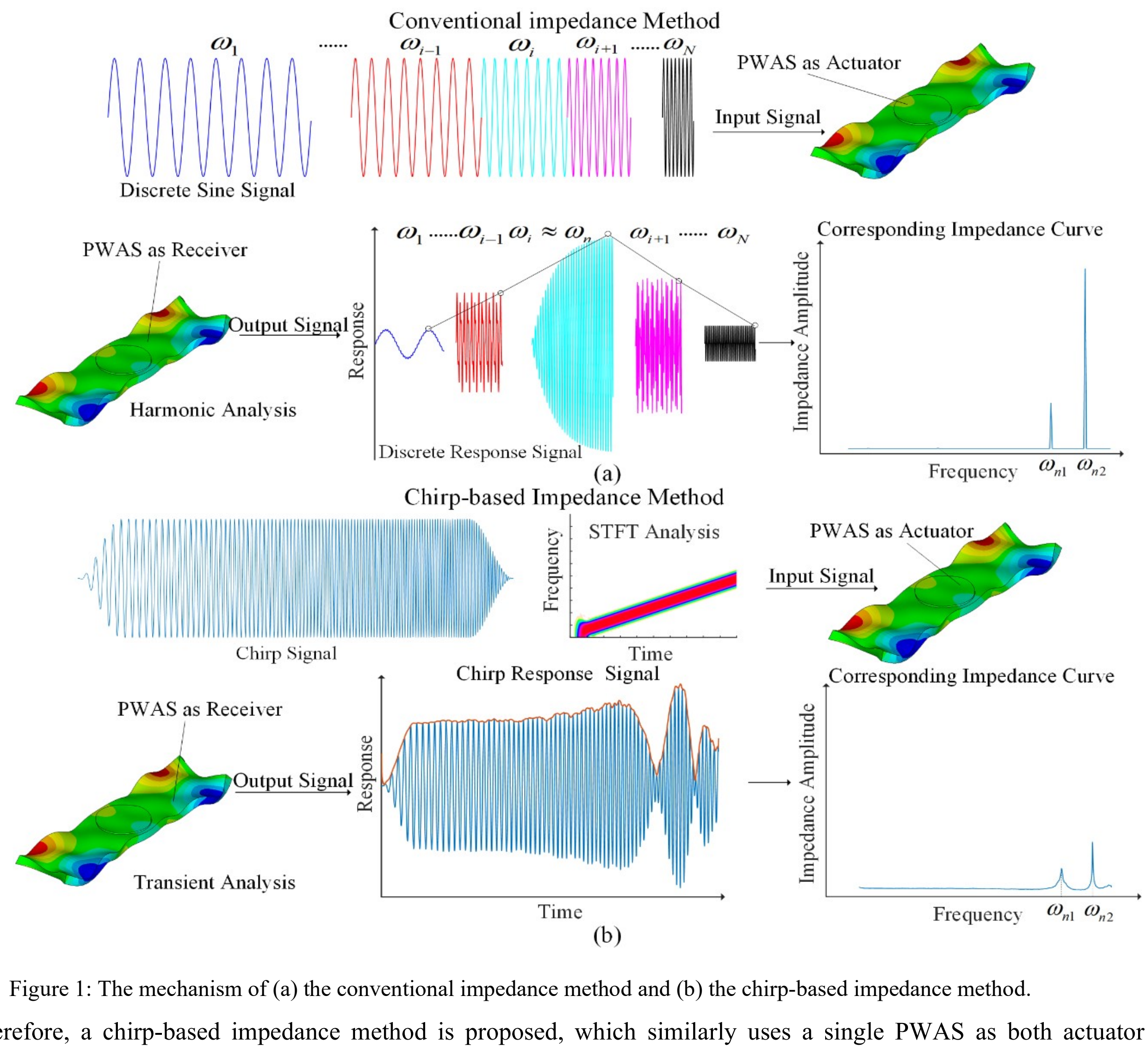

Figure 1: The mechanism of (a) the conventional impedance method and (b) the chirp-based impedance method.

Therefore, a chirp-based impedance method is proposed, which similarly uses a single PWAS as both actuator and receiver. Different from the discrete frequency input, the input signal of this method is a frequency sweeping chirp signal containing rich time-history information. That is to say one chirp signal with relatively short duration, can also obtain the impedance spectra, the procedure of which is displayed in Figure 1(b). Regarding the specific numerical implementation in the finite element procedure, the transient electrical charge at multi-physics element is obtained first. According to the relationship $I = {dQ}/{dt}$, the current flowing through the electrodes can be calculated, the amplitude of which is captured by an envelope curve. Applying the equation $R = {V_{chirp}}/{I_{envelope}}$, where V is a constant amplitude of the input chirp signal, the chirp-based impedance spectrum can be finally obtained (last figure in Figure 1(b)).

2.2 Numerical investigation on nonlinear features of the CAN model

It is necessary to develop an in-depth understanding of the phenomena and mechanism of nonlinear wave damage interaction for better comprehension and appreciation of the NEMIS method. Contact acoustic nonlinearity (CAN) stems from the contact dynamic behavior of the two interfaces experiencing periodic collisions, resulting in the change of local structural stiffness. The bilinear model for nonlinear ultrasonic wave-crack interaction has been extensively investigated for the simulation of breathing cracks [47, 48]. Furthermore, Wang et al. proposed a nonlinear oscillator model with a transitional region to capture the rough crack surface features, which is closer to a practical situation [37]. Based on this model shown in Figure 2(a), a numerical study using central difference computation is conducted to capture the nonlinear ultrasonic phenomenon.

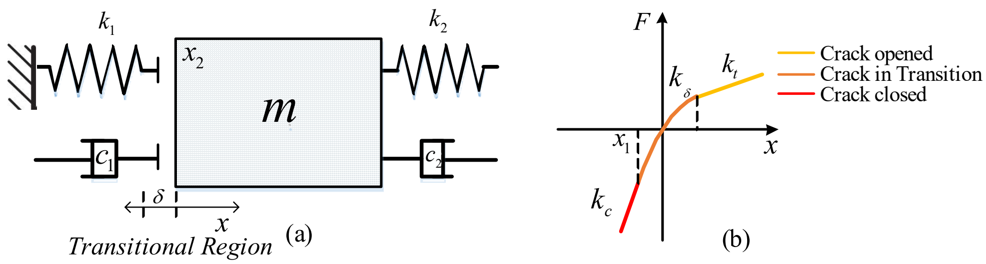

Figure 2: (a) The CAN model with transitional region and (b) the local stiffness curve of the model.

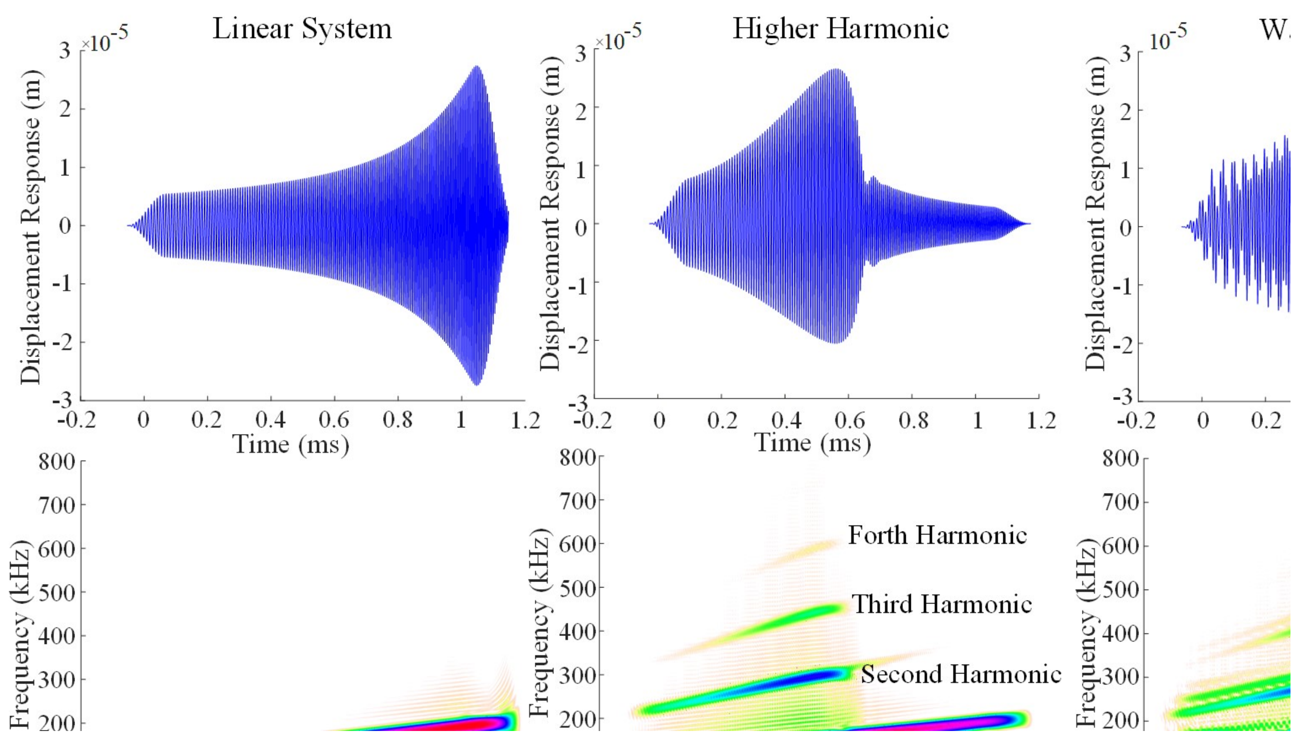

Figure 3: The temporal displacement response and the corresponding time-frequency representation of (a) the linear system; (b) the nonlinear system with pure chirp excitation; (c) the nonlinear system with mixed chirp excitation.

The temporal responses of the system are obtained as displayed in Figure 3. For the linear system shown in Figure 3(a), the frequency components of the output are consistent with the input signal, which is 100-200 kHz. Regarding the nonlinear system, the higher harmonic components resulting from the CAN, second harmonic (200-400 kHz), third harmonic (300-600 kHz), and forth harmonic (400-800 kHz) are generated and displayed in Figure 3(b). Regarding the wave modulation phenomenon, the low frequency sine signal interacts with the chirp signal, generating several side-band as is marked in Figure 3(c). The numerical analysis demonstrates the feasibility of employing the chirp signal to conduct nonlinear ultrasonic method for the detection of fatigue cracks.

3. NUMERICAL VALIDATION OF THE CHIRP-BASED IMPEDANCE CURVE

In commercial FEM software ANSYS, a general beam model was established to explore the chirp-based impedance algorithm and its capability to capture nonlinear responses from an ideal breathing crack. The material of the beam was aluminum and the PWAS was bonded in the middle of the top surface as shown in Figure 4.

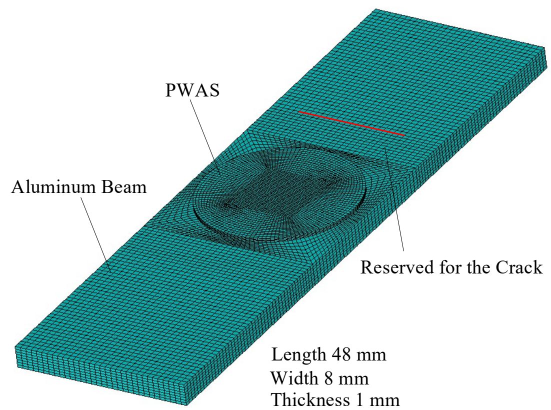

Figure 4: The finite element model layout for NEMIS investigation.

The fundamental function of the chirp-based impedance method was to obtain the impedance spectrum, which should be verified on the pristine model of the beam. Firstly, a harmonic analysis was conducted, sweeping from 300 kHz to 400 kHz. The impedance spectrum from harmonic analysis was regarded as the standard version (conventional EMIS). Then, the chirp-based impedance algorithm was applied. Exciting the PWAS using a chirp voltage signal, the electrical charge in temporal domain at the PWAS terminal was acquired (Figure 5(a)), from which the current could be derived through $I = dQ / dt$ (Figure 5 (b)). The relatively low value at the beginning originated from the Tukey Window imposed on the excitation signal. The envelope curve of the current was generated to capture the amplitude information. Since the frequency of the chirp signal increases linearly, the temporal x-coordinate could be mapped onto the spectral coordinate. By invoking $R = V / I$, the impedance spectrum was finally obtained (Figure 5(c)).

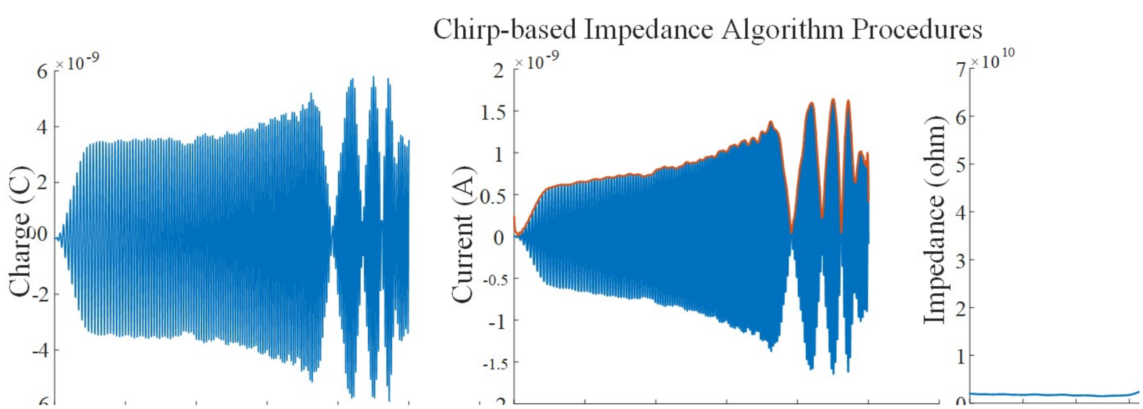

Figure 5: (a) The electrical charge response at the PWAS terminal; (b) the calculated current response; (c) the corresponding chirp-based impedance spectra.

The comparative impedance spectra are presented in Figure 6. It can be observed that the impedance amplitude values from the two methods are different. This is because, the electrical charge obtained from transient analysis cannot fully capture the steady-state response. Nevertheless, the resonance frequencies, at approximately 355 kHz, 373 kHz, and 382 kHz, are in good agreement for the two methods despite the difference in the absolute values. The proposed chirp-based method would approach the steady-state response, given a sufficiently long excitation duration. Yet, it will lose the time-history information, which is a key factor for nonlinear ultrasonic inspection. It should be emphasized here that the purpose of the proposed chirp algorithm is not for replacing the conventional, accurate measurement of electro-mechanical impedance method. It aims to depict the impedance trends while embraces the capability to obtain the nonlinear information as an enrichment for structural diagnostics, even forming a baseline free approach.

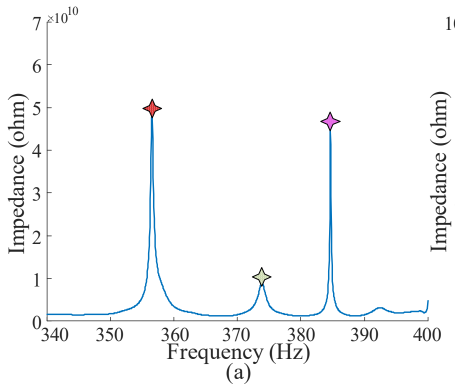

Figure 6: Impedance spectra from (a) chirp-based envelope algorithm; (b) conventional harmonic analysis.

4. EXPERIMENTAL INVESTIGATION OF NEMIS FOR FATIGUE CRACK MONITORING

In this section, experiments were conducted to verify the feasibility of the chirp-based impedance algorithm and NEMIS for fatigue crack monitoring. The overall experiment layout is displayed below. To collect the required data, an auxiliary circuit (shown in Figure 7(c)) was designed to cooperate with the oscilloscope and the function generator. The divider resistor R_1 was employed to obtain the current ($I = V_2 / R_1$) while the voltage on the PWAS was acquired by $V_{PWAS} = V_1 - V_2$, through which, the impedance can then be calculated. The aluminum beam was suspended by two ropes to approximate the free-free boundary condition as displayed in Figure 7(a). The fatigue crack was generated by cyclic loading on the MTS machine.

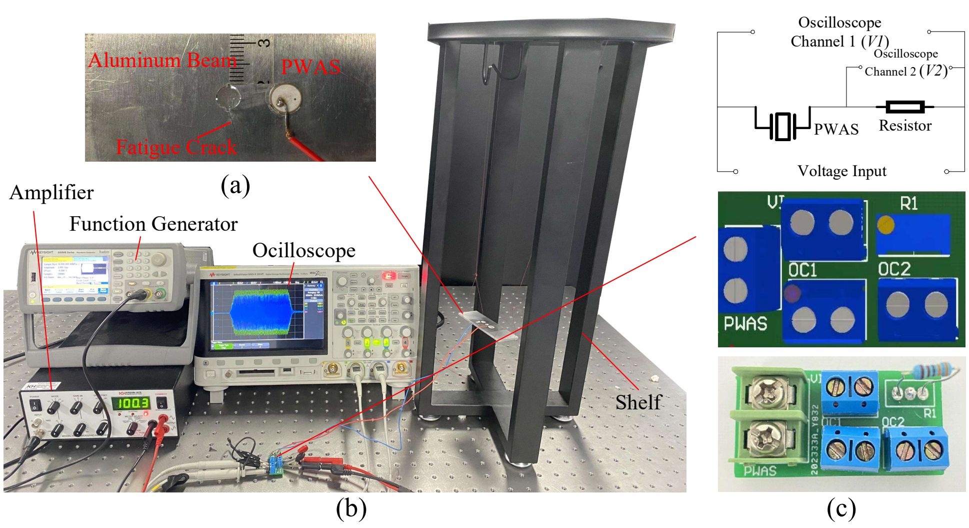

Figure 7: (a) the aluminum beam specimen with a fatigue crack; (b) the overall experimental setting; (c) the design and entity of the auxiliary circuit for electrical quantity measurements.

4.1 Experimental validation of the Chirp-based Impedance Algorithm

Four different beams were used to verify the chirp-based impedance method. The chirp-based impedance spectra were obtained as Figure 8 illustrates. The excitation voltage (V_1) was a linear chirp signal from 100 kHz to 200 kHz with a time duration of 0.1 second. Voltage on PWAS was acquired by subtracting the voltage of the resistor (V_2) from the whole voltage (V_1) and the envelope curve was simultaneously obtained. The Voltage in time domain was transferred into frequency domain (100-200 kHz) through the linear mapping from time to frequency. The current on the series circuit was calculated through the formula $I = V_2 / R_1$. Finally, the enveloped voltage value and the enveloped current value were used to obtain the chirp-base impedance spectrum.

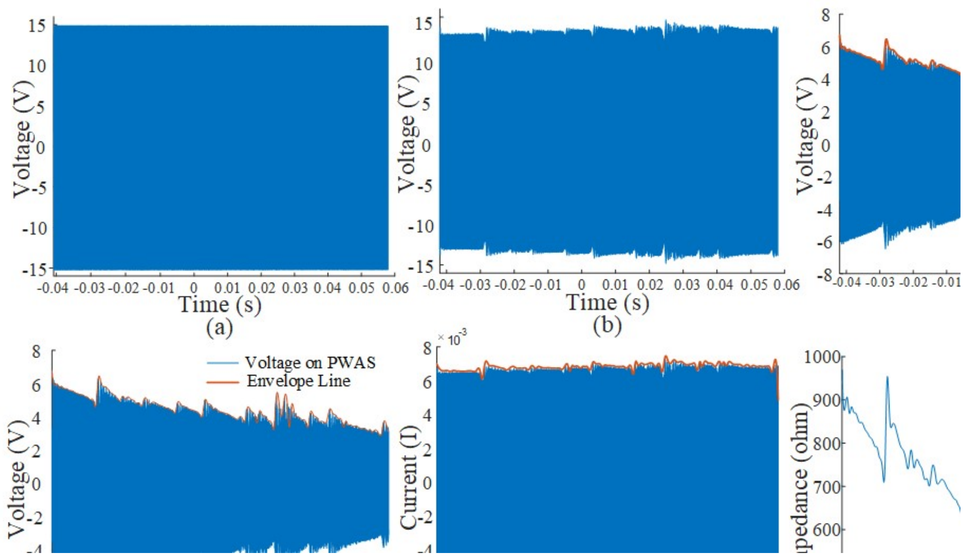

Figure 8: (a)/(b) The voltage measured from the oscilloscope channel 1/2; (c)/(d) the voltage on PWAS for time domain/frequency domain; (e) the current on the series circuit; (f) the chirp-based impedance spectrum.

Impedance spectra obtained from the BODE 100 impedance analyzer functioned as the benchmark to be compared with. Four comparative experiments were conducted on different aluminum beams to verify the chirp-based impedance features, as shown in Figure 9. Generally, the main resonance peaks from both methods can correspond to each other with negligible errors.

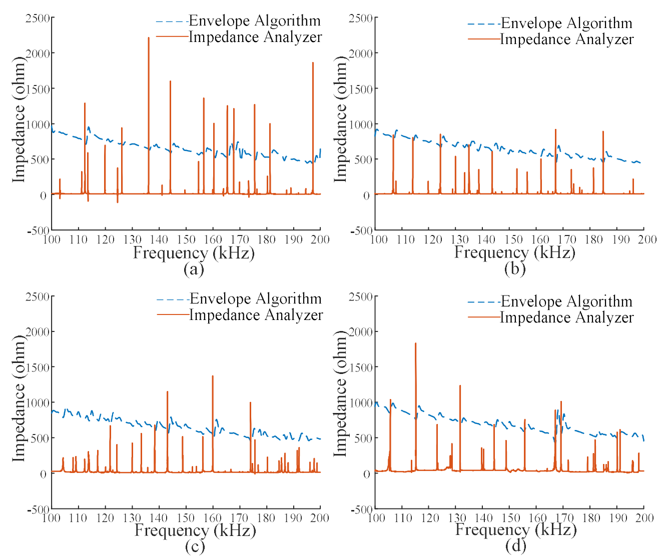

Figure 9: Impedance comparison between the chirp-based method and the impedance analyzer for different beam specimens.

4.2 Application of NEMIS for Fatigue Crack Monitoring

The nonlinear chirp-based impedance algorithm aims at detecting the existence of fatigue cracks and further quantify their severity. The transient voltage data containing frequency information and the current envelope values containing the amplitude information were captured to calculate the transient nonlinear impedance signature. Then, Fast Fourier Transformation was conducted on the transient data to obtain the nonlinear impedance spectra at the frequency domain. In this experiment, the excitation signal was tailored with a mixture of a chirp signal from 68.75 kHz to 81.25 kHz and a pure sine signal of 30 kHz lasting for 10 ms as shown in Figure 10. A Tukey window was exerted to avoid frequency leakage from sudden signal changes. When processing the signal, only 80% of the entire response was extracted from the original signal to obtain the response from 70 kHz to 80 kHz frequency components to get rid of the unwanted nonlinearity from the instrument and external disturbances.

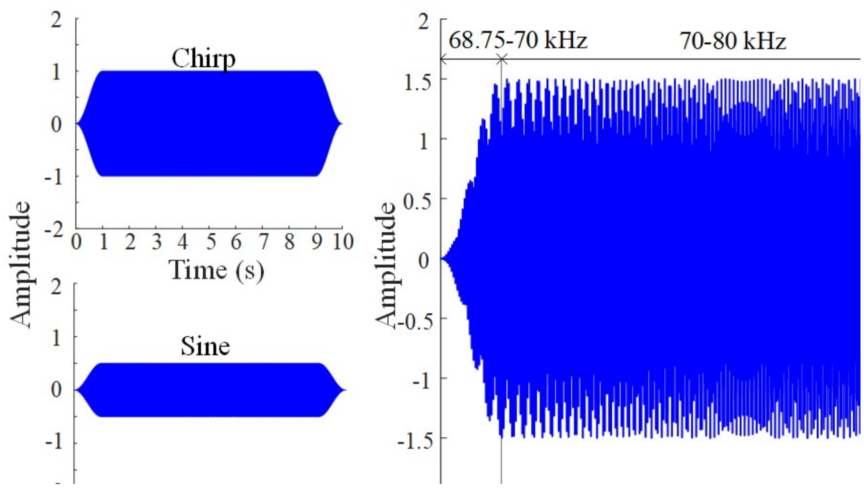

Figure 10: (a) a chirp signal from 68.75-81.25 kHz and a sine signal of 30 kHz modulated by a Tukey window function; (b) mixed excitation signal.

As for the fatigue cracks on the aluminum beam, they were generated by the MTS machine with cyclic sinusoidal loadings of 7 KN at the frequency of 12 kHz. The total cyclic number was 50,000 with a measurement interval of 10,000 times. The MTS machine setup and the specimen with fatigue cracks were showcased in Figure 11.

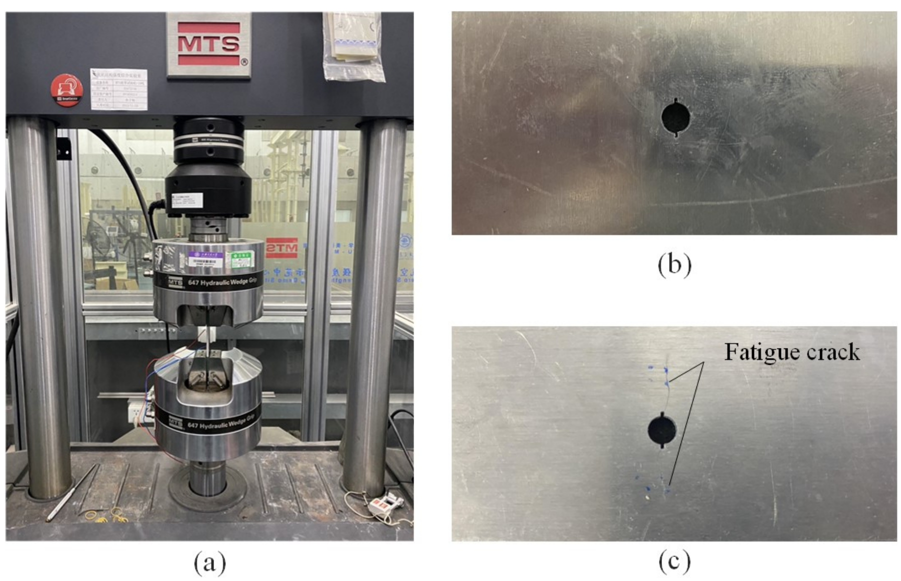

Figure 11: (a) the fatigue test on MTS machine; (b) the pristine aluminum beam specimen; (c) the specimen after 50 thousand loading cycles with an obvious fatigue crack.

Then NEMIS was conducted for detection and quantification of the fatigue crack. As mentioned in the theoretical part, higher harmonic components and wave modulation would appear at the presence of incipient cracking. For the employed mixed chirp excitation signal, consisting of a chirp from 70 kHz to 80 kHz and a pure sine of 30 kHz, the second harmonic of the sine signal and wave modulation components of the chirp signal were to be captured. Specifically, the second harmonic was 60 kHz (2*30 kHz); the wave modulation of the fundamental chirp was 100-110 kHz (70-80 kHz +30 kHz); the wave modulation of the second harmonic chirp was 170-190 kHz (140-160 kHz +30 kHz). The logarithmic impedance spectra for different damage cases were displayed in Figure 12(a). A single impedance spectrum was extracted to illustrate the higher harmonic and wave modulation components in Figure 12(b). It is worth mentioning that each nonlinear impedance spectrum can generate a chaos-defused baseline for nonlinearity quantification purpose.

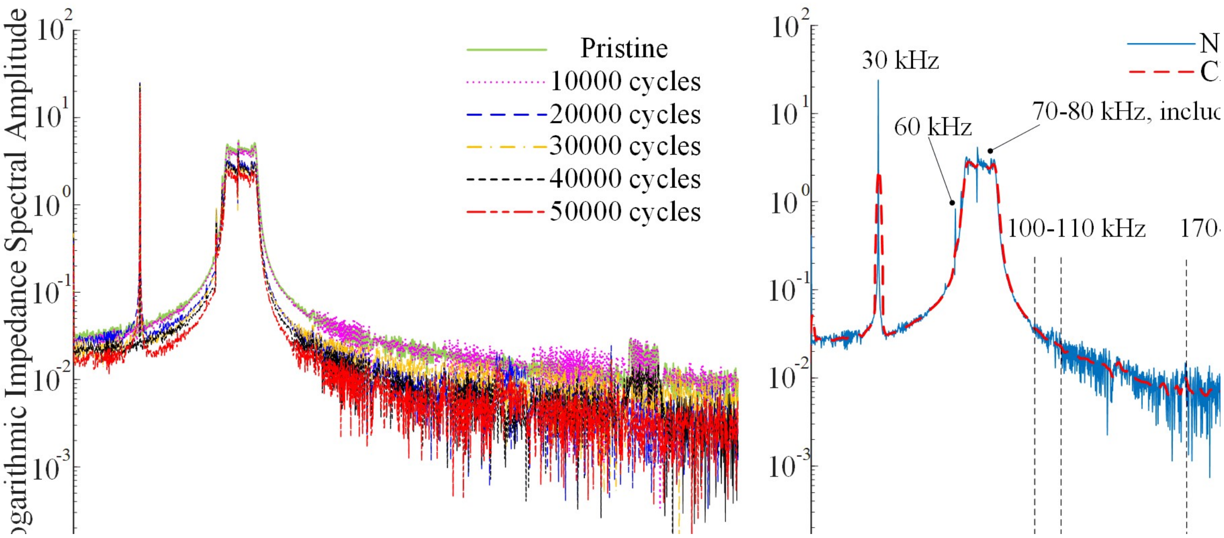

Figure 12: (a) the expanded nonlinear impedance spectra for the specimen under different loading cycles; (b) a single impedance spectrum to illustrate nonlinear features with its chaos-defused baseline.

The severity of the damage is evaluated by the degree of chaos within the wave modulation frequency ranges. The level of signal disorder is associated with the extent of system nonlinearity, which is explained by the chaos theory [49]. To quantify the severity of the damage, a nonlinear damage index is designed: Baseline Deviation Index (BDI). BDI evaluates the level of the vibration and chaos of the impedance curve at a certain frequency range by measuring its deviation from the chaos-defused baseline, as can be seen in Figure 12(b).

$$BDI = \frac{\sum (R - R_0)^2}{\sum R_0^2} \tag{1}$$

where R denotes the impedance value, while R_s stands for the chaos-defused baseline value. BDI is employed to quantify the severity of the damage via different nonlinear phenomena. As explained in the introduction part, before the existence of real fatigue cracks, the dislocation, friction, and stress concentration resulting from the initial generation of the crack can lead to the nonlinear wave modulation. These are reflected on the BDI curves shown in Figure 13.

It should be noted that, even for the pristine specimen, the slight inherent nonlinearity due to the equipment and adhesive layers still exists and is hard to be completely eliminated. As for wave modulation components shown in Figure 13, the BDI value displayed a general monotonic growth due to the increasing severity of the fatigue crack in spite of a decrease at 30,000 cycles for 110-110 kHz frequency components.

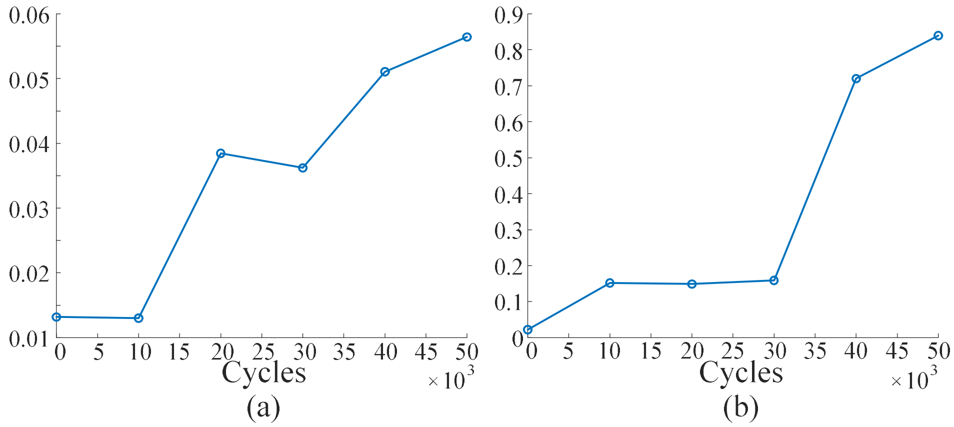

Figure 13: (a) BDI value for wave modulation 100-110 kHz; (b) BDI value for wave modulation 170-190 kHz.

5. CONCLUDING REMARKS AND FUTURE WORK

This paper presented a chirp-based nonlinear impedance spectroscopy for the fatigue crack monitoring and quantification. This method combined the merit of conventional impedance method and nonlinear ultrasonics. A comparative illustration between the conventional impedance method and NEMIS was displayed to develop an in-depth understating into the mechanism. A bilinear CAN model with transitional region was established to conduct the numerical study of the chirp-based nonlinear ultrasonic phenomenon. Furthermore, an aluminum beam model was established in commercial FEM software to verify the feasibility of the chirp-based impedance algorithm. After the theoretical and numerical investigations, a series of experiments were conducted to validate the performance of the chirp-based impedance method and the effectiveness for fatigue crack monitoring. It was found that the chirp-based impedance method attained a good match compared with the benchmark spectra from the impedance analyzer. NEMIS was employed to obtain the impedance spectra containing nonlinear components. Similar to the numerical study, nonlinear modulation frequency components were applied to detect the existence of the fatigue crack. Each impedance spectrum could generate a chaos-defused baseline by itself. The severity of the damage was quantified by degree of chaos in the impedance curve; its deviation from the chaos-defused baseline was used as the nonlinear measurement. The result showed that the proposed NEMIS approach can detect and quantify fatigue cracks using only one PWAS transducer.

For future work, the application of NEMIS method should be applied for damage detection in composite structures. Moreover, the linear resonance information and the nonlinear features should be combined to form a more comprehensive damage detection strategy.

6. ACKNOWLEDGMENTS

The support from the National Natural Science Foundation of China (contract numbers 51605284 and 51975357) is thankfully acknowledged; this research is also sponsored by the Shanghai Rising-star Program (contract number 21QA1405100).

REFERENCES

[1] R. Sun, E. Sevillano, and R. Perera, "Identification of intermediate debonding damage in FRP-strengthened RC beams based on a multi-objective updating approach and PZT sensors," *Composites Part B: Engineering,* vol. 109, pp. 248-258, 2016, doi: 10.1016/j.compositesb.2016.10.060.

[2] A. V. G. Madhav and C. K. Soh, "An electromechanical impedance model of a piezoceramic transducer-structure in the presence of thick adhesive bonding," *Smart Materials and Structures,* vol. 16, no. 3, pp. 673-686, 2007, doi: 10.1088/0964-1726/16/3/014.

[3] C. Zuo, X. Feng, Y. Zhang, L. Lu, and J. Zhou, "Crack detection in pipelines using multiple electromechanical impedance sensors," *Smart Materials and Structures,* vol. 26, no. 10, 2017, doi: 10.1088/1361-665X/aa7ef3.

[4] M. Gresil, L. Yu, V. Giurgiutiu, and M. Sutton, "Predictive modeling of electromechanical impedance spectroscopy for composite materials," *Structural Health Monitoring: An International Journal,* vol. 11, no. 6, pp. 671-683, 2012, doi: 10.1177/1475921712451954.

[5] G. Park, H. H. Cudney, and D. J. Inman, "Feasibility of using impedance-based damage assessment for pipeline structures," *Earthquake Engineering & Structural Dynamics,* vol. 30, no. 10, pp. 1463-1474, 2001, doi: 10.1002/eqe.72.

[6] A. Croxford, P. Wilcox, B. Drinkwater, and P. Nagy, "The use of non-collinear mixing for nonlinear ultrasonic detection of plasticity and fatigue," *The Journal of the Acoustical Society of America,* vol. 126, pp. 17-22, 2009, doi: 10.1121/1.3231451.

[7] C. Boller, "Ways and options for aircraft structural health management," *Smart Materials and Structures,* vol. 10, p. 432, 06/08 2001, doi: 10.1088/0964-1726/10/3/302.

[8] K. Worden, C. Farrar, and G. Manson, "The Fundamental Axioms of Structural Health Monitoring," *Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 463, pp. 1639-1664, 06/08 2007, doi: 10.1098/rspa.2007.1834.

[9] J. He and G. Yuan, "Damage identification for composite structures using a cross-correlation reverse-time migration technique," *Structural Health Monitoring,* vol. 2, 09/11 2015, doi: 10.1177/1475921715602546.

[10] S.-J. Lee, "Lamb wave tuning curve calibration for surface-bonded pzt transducers," *Struct,* vol. 19, pp. 15007-12, 01/01 2010, doi: 10.1088/0964-1726/19/1/015007.

[11] A. C. Raghavan and C. Cesnik, "Review of Guided-Wave Structural Health Monitoring," *The Shock and Vibration Digest,* vol. 39, pp. 91-114, 03/01 2007, doi: 10.1177/0583102406075428.

[12] L. Yu, G. Santoni, and V. Giurgiutiu, "Shear lag solution for tuning ultrasonic piezoelectric wafer active sensors with applications to Lamb wave array imaging," *International Journal of Engineering Science - INT J ENG SCI,* vol. 48, pp. 848-861, 10/01 2010, doi: 10.1016/j.ijengsci.2010.05.007.

[13] S. Yin, Z. Cui, and T. Kundu, "Acoustic source localization in anisotropic plates with "Z" shaped sensor clusters," *Ultrasonics,* vol. 84, 10/01 2017, doi: 10.1016/j.ultras.2017.10.007(

[14] J.-Y. Kim, L. Jacobs, J. Qu, G. Woodruff, and J. Littles, "Experimental characterization of fatigue damage in a nickel-base superalloy using nonlinear ultrasonic waves," *Ba MFH Pages,* vol. 120, pp. 1266-1273, 09/01 2006, doi: 10.1121/1.2221557.

[15] Z. Su, C. Zhou, M. Hong, L. Cheng, Q. Wang, and X. Qing, "Acousto-ultrasonics-based fatigue damage characterization: Linear versus nonlinear signal features," *Mechanical Systems and Signal Processing,* vol. 45, no. 1, pp. 225-239, 2014, doi: 10.1016/j.ymssp.2013.10.017.

[16] J. Cantrell and W. Yost, "Nonlinear ultrasonic characterization of fatigue microstructures," *International Journal of Fatigue,* vol. 23, pp. 487-490, 02/01 2001, doi: 10.1016/S0142-1123(01)00162-1.

[17] F. Aymerich and W. Staszewski, "Experimental Study of Impact-Damage Detection in Composite Laminates using a Cross-Modulation Vibro-Acoustic Technique," *Structural Health Monitoring-an International Journal - STRUCT HEALTH MONIT,* vol. 9, 10/18 2010, doi: 10.1177/1475921710365433.

[18] H. J. Lim, M. Desimio, and K. Brown, "Reference-free fatigue crack detection using nonlinear ultrasonic modulation under various temperature and loading conditions," *Mechanical Systems and Signal Processing,* vol. 45, pp. 468–478, 04/01 2014, doi: 10.1016/j.ymssp.2013.12.001.

[19] P. Liu, H. Sohn, and I. Jeon, "Nonlinear spectral correlation for fatigue crack detection under noisy environments," *Journal of Sound and Vibration,* 2017, doi: 10.1016/j.jsv.2017.04.021.

[20] D. Donskoy, A. Sutin, and A. Ekimov, "Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing," *NDT & E International,* vol. 34, pp. 231-238, 06/01 2001, doi: 10.1016/S0963-8695(00)00063-3.

[21] P. Duffour, M. Morbidini, and P. Cawley, "A study of the vibro-acoustic modulation technique for the detection of cracks in metals," *The Journal of the Acoustical Society of America,* vol. 119, p. 1463, 03/01 2006, doi: 10.1121/1.2161429.

[22] A. Klepka, W. Staszewski, R. Jenal, M. Szwedo, J. Iwaniec, and T. Uhl, "Nonlinear acoustics for fatigue crack detection – experimental investigations of vibro-acoustic wave modulations," *Structural Health Monitoring,* vol. 11, pp. 197-211, 07/25 2011, doi: 10.1177/1475921711414236.

[23] H. Sohn, H. J. Lim, M. P. DeSimio, K. Brown, and M. Derriso, "Nonlinear ultrasonic wave modulation for online fatigue crack detection," *Journal of Sound and Vibration,* vol. 333, no. 5, pp. 1473-1484, 2014/02/28/ 2014, doi: 10.1016/j.jsv.2013.10.032.

[24] J.-Y. Kim, A. Baltazar, J. Hu, and S. Rokhlin, "Hysteretic linear and nonlinear acoustic responses from pressed interfaces," *International Journal of Solids and Structures - INT J SOLIDS STRUCT,* vol. 43, pp. 6436-6452, 10/01 2006, doi: 10.1016/j.ijsolstr.2005.11.006.

[25] M. Zhang, Y. Shen, L. Xiao, and W. Qu, "Application of subharmonic resonance for the detection of bolted joint looseness," *Nonlinear Dynamics,* vol. 88, no. 3, pp. 1643-1653, 2017/05/01 2017, doi: 10.1007/s11071-017-3336-1.

[26] I. Solodov, J. Wackerl, K. Pfleiderer, and G. Busse, "Nonlinear self-modulation and subharmonic acoustic spectroscopy for damage detection and location," *Applied Physics Letters,* vol. 84, pp. 5386-5388, 06/17 2004, doi: 10.1063/1.1767283.

[27] Y. Yang, C.-T. Ng, A. Kotousov, H. Sohn, and H. J. Lim, "Second harmonic generation at fatigue cracks by low-frequency Lamb waves: Experimental and numerical studies," *Mechanical Systems and Signal Processing,* vol. 99, pp. 760-773, 01/15/ 2018, doi: 10.1016/j.ymssp.2017.07.011.

[28] S. M. Hogg, B. E. Anderson, P.-Y. Le Bas, and M. C. Remillieux, "Nonlinear resonant ultrasound spectroscopy of stress corrosion cracking in stainless steel rods," *NDT & E International,* vol. 102, pp. 194-198, 2019/03/01/ 2019, doi: 10.1016/j.ndteint.2018.12.007.

[29] M. Meo, U. Polimeno, and G. Zumpano, "Detecting Damage in Composite Material Using Nonlinear Elastic Wave Spectroscopy Methods," *Applied Composite Materials,* vol. 15, no. 3, pp. 115-126, 05/01 2008, doi: 10.1007/s10443-008-9061-7.

[30] B. Masserey and P. Fromme, "Fatigue crack growth monitoring using high-frequency guided waves," *Structural Health Monitoring,* vol. 12, pp. 484-493, 12/20 2013, doi: 10.1177/1475921713498532.

[31] P. Liu, H. Sohn, S. Yang, and H. J. Lim, "Baseline-free fatigue crack detection based on spectral correlation and nonlinear wave modulation," *Smart Materials and Structures,* vol. 25, no. 12, 11/14 2016, doi: 10.1088/0964-1726/25/12/125034.

[32] A. Klepka *et al.*, "Triple correlation for detection of damage-related nonlinearities in composite structures," *Nonlinear Dynamics,* vol. 81, 07/01 2015, doi: 10.1007/s11071-015-2004-6.

[33] P. Liu, J. Jang, S. Yang, and H. Sohn, "Fatigue crack detection using dual laser induced nonlinear ultrasonic modulation," *Optics and Lasers in Engineering,* vol. 110, pp. 420-430, 11/01/ 2018, doi: 10.1016/j.optlaseng.2018.05.025.

[34] T. Stratoudaki, R. Ellwood, S. Sharples, M. Clark, M. Somekh, and I. Collison, "Measurement of material nonlinearity using surface acoustic wave parametric interaction and laser ultrasonics," *The Journal of the Acoustical Society of America,* vol. 129, pp. 1721-8, 04/01 2011, doi: 10.1121/1.3560945.

[35] J. Wang, Y. Shen, R. Danyu, and W. Xu, "Physical-virtual time reversing of nonlinear Lamb waves for fatigue crack detection and quantification," *Mechanical Systems and Signal Processing,* vol. 160, p. 107921, 11/01 2021, doi: 10.1016/j.ymssp.2021.107921.

[36] E. Barbieri and M. Meo, "Discriminating linear from nonlinear elastic damage using a nonlinear time reversal DORT method," *International Journal of Solids and Structures,* vol. 47, pp. 2639-2652, 10/01 2010, doi: 10.1016/j.ijsolstr.2010.05.008.

[37] J. Wang, Y. Shen, R. Danyu, and W. Xu, "An instantaneous-baseline multi-indicial nonlinear ultrasonic resonance spectral correlation technique for fatigue crack detection and quantification," *Nonlinear Dynamics,* vol. 103, 01/01 2021, doi: 10.1007/s11071-020-06128-x.

[38] W. Xu, Z. Su, M. Radzienski, M. Cao, and W. Ostachowicz, "Nonlinear pseudo-force in a breathing crack to generate harmonics," *Journal of Sound and Vibration,* vol. 492, p. 115734, 02/01 2021, doi: 10.1016/j.jsv.2020.115734.

[39] D. Broda, W. Staszewski, A. Martowicz, T. Uhl, and V. Silberschmidt, "Modelling of nonlinear crack–wave interactions for damage detection based on ultrasound—A review," *Journal of Sound and Vibration,* vol. 333, pp. 1097–1118, 02/01 2014, doi: 10.1016/j.jsv.2013.09.033.

[40] Y. Shen and C. Cesnik, "Modeling of Nonlinear Interactions between Guided Waves and Fatigue Cracks Using Local Interaction Simulation Approach," *Ultrasonics,* vol. 74, 10/01 2016, doi: 10.1016/j.ultras.2016.10.001.

[41] R. Radecki, Z. Su, P. Packo, and W. Staszewski, "Modelling Nonlinearity of Guided Ultrasonic Waves in Fatigued Materials Using a Nonlinear Local Interaction Simulation Approach and a Spring Model," *Ultrasonics,* vol. 84, 11/01 2017, doi: 10.1016/j.ultras.2017.11.008.

[42] C. Lissenden, "Nonlinear ultrasonic guided waves—Principles for nondestructive evaluation," *Journal of Applied Physics,* vol. 129, 01/14 2021, doi: 10.1063/5.0038340.

[43] B. Bullecks, R. Suresh, and R. Rengaswamy, "Rapid impedance measurement using chirp signals for electrochemical system analysis," *Computers & Chemical Engineering,* vol. 106, 06/01 2017, doi: 10.1016/j.compchemeng.2017.05.018.

[44] P. Slepski, "Optimization of impedance measurements using 'chirp' type perturbation signal," *Measurement,* vol. 42, pp. 1220-1225, 10/01 2009, doi: 10.1016/j.measurement.2009.06.005.

[45] T. Saar, M. Reidla, O. Martens, R. Land, M. Min, and H. Herranen, "Chirp-based piezo-impedance measurement," in *2013 IEEE 8th International Symposium on Intelligent Signal Processing, WISP 2013 - Proceedings*, Funchal, Portugal, 2013, pp. 83-86, doi: 10.1109/WISP.2013.6657487.

[46] V. Giurgiutiu, "Chapter 9 - PWAS Resonators," in *Structural Health Monitoring with Piezoelectric Wafer Active Sensors (Second Edition)*, V. Giurgiutiu Ed. Oxford: Academic Press, 2014, pp. 445-507.

[47] J.-Y. Kim, A. Baltazar, J. W. Hu, and S. I. Rokhlin, "Hysteretic linear and nonlinear acoustic responses from pressed interfaces," *International Journal of Solids and Structures,* vol. 43, no. 21, pp. 6436-6452, 10/01/ 2006, doi: 10.1016/j.ijsolstr.2005.11.006.

[48] J. Jin, P. Johnson, and P. Shokouhi, "An integrated analytical and experimental study of contact acoustic nonlinearity at rough interfaces of fatigue cracks," *Journal of the Mechanics and Physics of Solids,* vol. 135, p. 103769, 02/01/ 2020, doi: 10.1016/j.jmps.2019.103769.

[49] H. Mao, Y. Zhang, H. Mao, and Z. Huang, "Chaotic characteristics analysis of simulation signal of ultrasonic nonlinear modulation effect," in *Proceedings of the 2016 International Conference on Advanced Electronic Science and Technology*, Shenzhen, China, 2016, doi: 10.2991/aest-16.2016.30.