COVER SHEET

Title: Modeling and Experiments on Nonlinear Ultrasonic Guided Waves for Fatigue Crack Detection and Evaluation

Authors: Yanfeng Shen
Yiran Tian
Junzhen Wang
Mingjing Cen

ABSTRACT

This paper reports the recent modeling and experimental endeavors on nonlinear ultrasonic guided waves for fatigue crack detection and evaluation in the Active Materials and Intelligent Structures (AMIS) lab at Shanghai Jiao Tong University. The progress on efficient modeling of Contact Acoustic Nonlinearity (CAN) using Local Interaction Simulation Approach (LISA) is first presented. The modeling results will illustrate the mechanism of higher harmonic generation as well as special feature related to the rough crack surface condition. Subsequently, the experimental investigations will be presented, striving to adopt the aforementioned nonlinear phenomena for fatigue crack detection and evaluation. The first experimental research effort aims at incorporating the wave control capability of metamaterials into the nonlinear ultrasonic SHM and NDE procedure. An ultrasonic bandgap meta-surface will be demonstrated for the elimination of inherent second harmonic to enhance the sensitivity and reliability of the nonlinear ultrasonic system. The second experimental effort adopts the nonlinear mode conversion and scattering features of guided waves at fatigue cracks for improved imaging of the damage using the Scanning Laser Doppler Vibrometry (SLDV). These research results show that nonlinear ultrasonic guided waves enable the effective detection and evaluation of fatigue cracks. The paper finishes with summary, concluding remarks, and suggestions for future work.

INTRODUCTION

Fatigue cracks exist as great menace to engineering structures, because they are barely visible and difficult to detect. Thus, the development of effective fatigue crack

---

Yanfeng Shen, University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, 200240, China, yanfeng.shen@sjtu.edu.cn
Yiran Tian, University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, 200240, China
Junzhen Wang, University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, 200240, China
Mingjing Cen, University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Shanghai, 200240, China

detection methodologies is of critical importance. Guided waves have been investigated as a powerful tool for Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) applications. When they interact with fatigue cracks, Contact Acoustic Nonlinearity (CAN) may arise [1]. The nonlinear ultrasonic techniques have been reported as a sensitive approach to detect incipient structural changes (such as fatigue cracks) through the generation of distinctive characteristics, such as sub/super harmonic generation, DC response, mixed frequency modulation response (sideband effects), and various frequency/amplitude dependent threshold behaviors [2]. Many pioneer research endeavors have been carried out using the nonlinear ultrasonics for fatigue crack detection. Klepka et al. adopted the nonlinear acoustics and wave modulation technique to identify fatigue cracks [3]. Hong et al. achieved accurate localization of a fatigue crack by the temporal nonlinear signal features [4]. Wu et al. explored using the nonlinear amplitude effect to construct instantaneous baseline for fatigue crack detection with the tomography imaging algorithm [5]. Liu et al. extracted the fatigue crack information using the noncontact measurements and nonlinear modulation method, which allowed the visualization of fatigue cracks using scanning laser vibrometry [6]. All these research results demonstrated the superb potential of nonlinear ultrasonics for fatigue damage detection and quantification. However, there still exist many challenges for the application of nonlinear ultrasonic techniques. More in-depth understanding of the nonlinear mechanism behind wave crack interaction is needed, which would benefit from the advancement of modeling methods. Inherent nonlinearity from electronic equipment arises as another critical issue to be addressed for more reliable diagnosis of fatigue damage. In addition, the endeavor to take advantage of nonlinear signal information should be further extended into existing mature SHM and NDE techniques.

This paper reports the recent modeling and experimental endeavors on nonlinear ultrasonic guided waves for fatigue crack detection and evaluation in the Active Materials and Intelligent Structures (AMIS) lab at Shanghai Jiao Tong University. It will focus on our efforts in acquiring an in-depth understanding of nonlinear ultrasonic techniques, addressing the challenges for their application, as well as developing new approaches for damage detection using nonlinear wave information.

EFFICIENT MODELING OF NONLINEAR ULTRASONICS

The development of an effective guided wave based SHM system cannot be achieved without an in-depth understanding of the wave mechanics and wave damage interaction features. This section presents the recent advancement of Local Interaction Simulation Approach considering the rough crack condition as well as the special nonlinear features associated with it.

Local Interaction Simulation Approach Considering Rough Crack Condition

LISA is a finite difference based formulation for the computation of wave dynamics. It has enjoyed a fast development by incorporating more and more modeling capabilities, such as anisotropic material property formulation, damping model, and GPU implementation [7]. Our group further extended LISA's modeling prowess by introducing the CAN and random contact pair parameters to simulate the rough crack condition. A practical fatigue crack surface differs much from the usual idealized assumption of smooth “breathing cracks” which has been widely adopted by many researchers. Such deviation may bring uncertainties and variation into the scattering procedure. Figure 1 presents the microscopic image of the fatigue crack. It can be observed that the crack surface is rough with a zigzag crack trace. At certain location, relatively large material voids can be seen, while at others the distance between the crack interfaces are much closer. Within the rough crack surface, initially closed areas also exist, indicating pre-stressed contact points. The initial openings and closures are distributed along the crack surface in a relatively random pattern. In order to capture the nature of such rough crack surfaces, randomly distributed initial gap functions were adopted for the contact pairs in the LISA model. A positive gap distance represents the initial openings and the negative gap distances corresponds to the initial closures with pre-stresses.

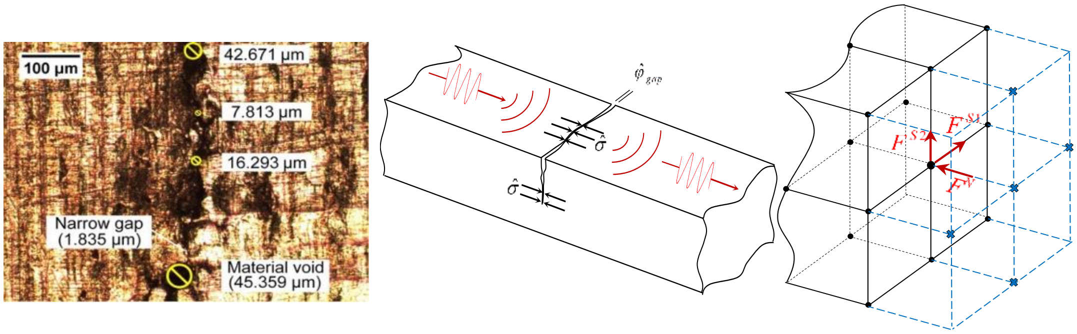

Figure 1: Microscopic image of a fatigue crack; initial openings and closures are implemented in the penalty method for modeling contact acoustic nonlinearity.

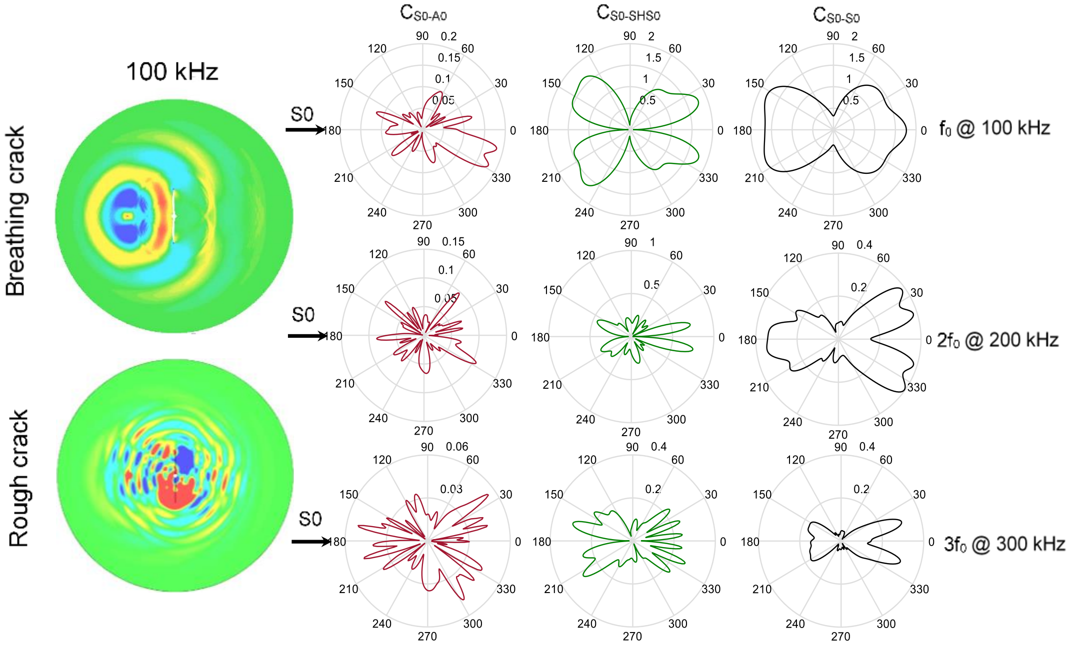

Figure 2: Random scattering and mode conversion features due to the crack roughness.

Special Nonlinear Features Associated with the Rough Crack Condition

The rough crack surface condition may give rise to the amplitude effect and random scattering directivity phenomenon. Figure 2 presents the wave scattering simulation results. Clear differences can be noticed between the idealized "breathing crack" case and the rough crack case. It can be observed that all possible wave modes participated in the scattering procedure. A0 mode aroused from mode conversion, which is quite different from the selective mode conversion phenomena for idealized breathing crack case, where the S0 mode can only be converted into symmetric modes (S0 and SHS0). Another remarkable difference is that the symmetry of the scattering pattern is broken. This is true for all the wave modes involved and especially obvious for the scattered A0 mode. The scattering coefficients take rather random patterns, which stems from the signature of the random initial opening and closure distribution along the crack line. All these special features may possess great application potential in nonlinear ultrasonic techniques if taken good use of [8].

METAMATERIALS FOR ELIMINATING INHERENT NONLINEARITY

After developing an in-depth understanding of the wave mechanics and wave damage interaction phenomena, the AMIS lab focused its efforts in resolving the challenges in nonlinear ultrasonic applications. This section presents a new approach to eliminating the inherent nonlinear higher harmonic influence for SHM and NDE applications. It allows the nonlinear traits from wave crack interactions to stand out, clearing off the influence of inherent nonlinearity from electronic equipment and adhesive materials.

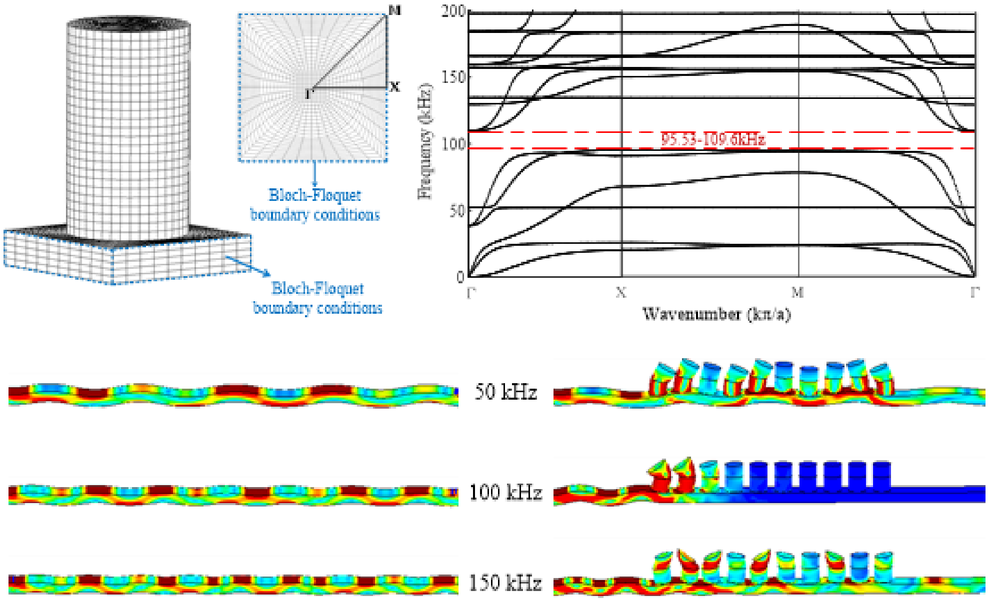

Figure 3: Bandgap metamaterials for the mechanical filtration of inherent second harmonics.

Metamaterials have been reported to possess superb capabilities in wave control. The AMIS lab has conducted a series of study, aiming at combining the wave control capability of metamaterials with guided wave based SHM techniques. Figure 3 shows the band structure of the designed metamaterial in all directions to guarantee a complete bandgap at the second harmonic frequency range. After the calculation, the complete bandgap ranging from 95.53-109.6 kHz satisfy the requirement, if the fundamental excitation happens around 50 kHz. Figure 3 also presents the equivalent stress responses of the smooth plate and the metamaterial structure at different frequencies (50 kHz, 100 kHz, and 150 kHz). The results demonstrate that the wave motion outside the bandgap can propagate through the metamaterial, while the frequency component within the bandgap will be effectively stopped and filtered away.

The metamaterial was implemented right after the transmitter. A pitch-catch active sensing experiment was conducted to relate the second harmonic amplitude with the crack size grown under fatigue loading. Figure 4 presents the experimental results. It can be observed that the amplitude started with an approximate zero value (after subtracting the noise base), indicating a pristine structure. Then, the amplitude grew monotonically with the increasing fatigue crack size. The results demonstrate an outstanding sensitivity and reliability of the improved damage detection strategy, with a clear threshold behavior for crack nucleation alarming and a nice monotonic trend for crack growth monitoring.

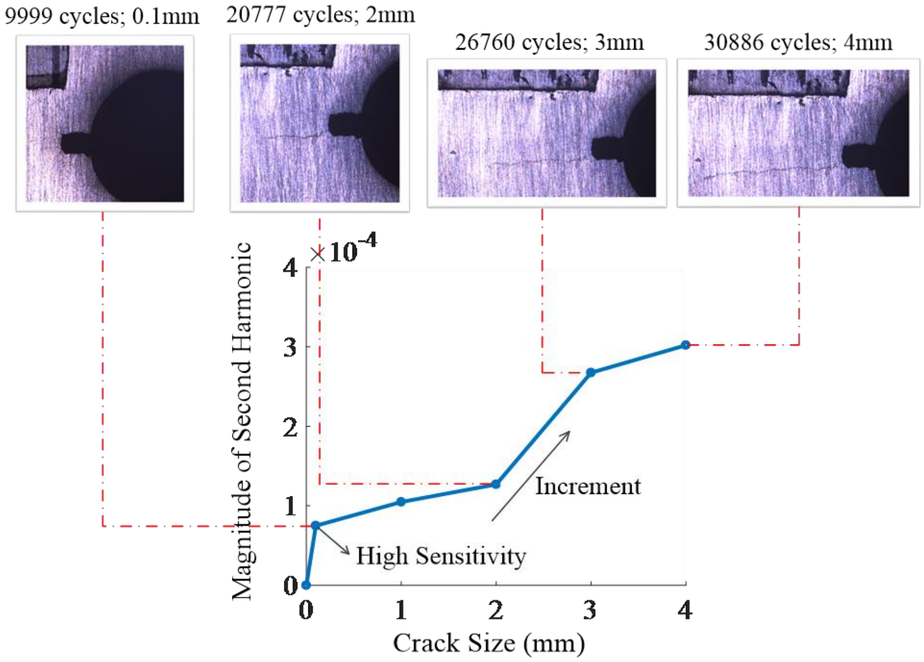

Figure 4: Reliable monitoring of crack nucleation and growth after the removal of inherent nonlinearity.

SCANNING LASER DOPPLER VIBROMETRY IMAGING OF FATIGUE CRACKS USING NONLINEAR ULTRASONICS

Scanning Laser Doppler Vibrometry (SLDV) has shown its superb capability in damage imaging for SHM and NDE [9]. The wave field images may provide straight forward information for damage detection and quantification. Thus, combining nonlinear ultrasonics with SLDV may facilitate the improved imaging and detection of fatigue cracks. The AMIS lab has conducted investigations for fatigue crack detection by extracting the nonlinear features from the scanning wave field data.

The nonlinear ultrasonic information from wave crack interaction was extracted via the signal post-processing. The procedure is realized in the following steps. First, the temporal signals are transformed into their corresponding frequency spectra through the Fast Fourier Transform (FFT). Then, these spectra are filtered with a frequency domain pass-window function centered at the second harmonic. After the filtration, the signal only contains the second harmonic component. Subsequently, inverse fast Fourier transform (IFFT) is performed on the signals, rendering the time traces of the nonlinear response. Finally, the spatial temporal domain wave field is visualized and further post processed via the energy amplitude to reveal the fatigue cracks.

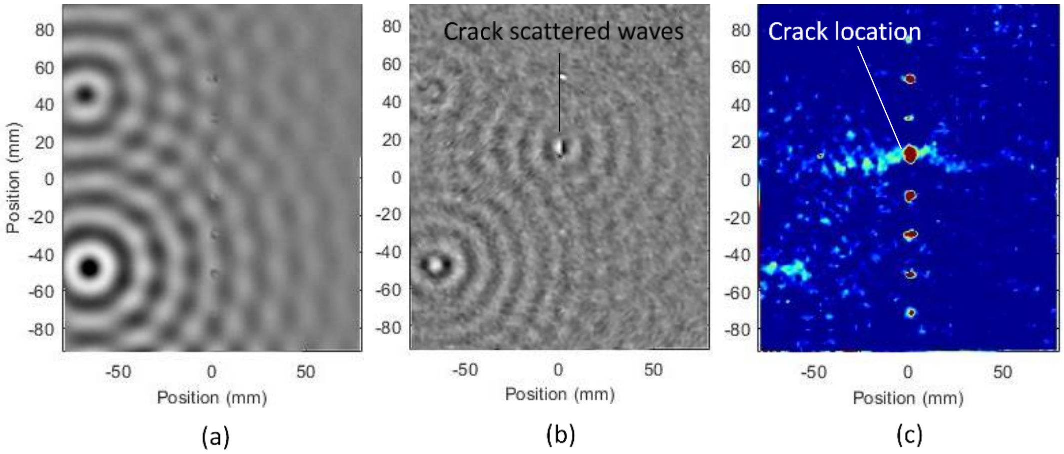

Figure 5: Improved imaging result of the fatigue crack: (a) linear wave field; (b) nonlinear wave field; (c) wave energy spatial distribution showing nonlinear wave sources.

Figure 5a shows the original wave field image, representing the conventional linear wave propagation. It can be clearly seen that the circular crested Lamb waves were generated by the transmitters. The interrogating wave field irradiated outwards, spreading across the specimen. The rivet holes can be noticeably identified from the SLDV image. On the other hand, the fatigue crack image is not clear and barely visible from the image. Figure 5b presents the nonlinear counterpart wave field image after the post-processing. Since the second harmonic resided at the second harmonic frequency, the wavelength became much shorter. It should be noted that the weak inherent nonlinearity brought by the electronic equipment and the adhesive layer participated in the wave generation. The generated second harmonic component can be obviously identified, irradiating from the transducer. It is remarkable that the localized nonlinear mode conversion and scattering wave field can be clearly visualized via the post-processing technique. Such scattered nonlinear A0 wave field stem from the mode conversion from S0 wave incidence on the fatigue crack. Meanwhile, the PWAS generated A0 nonlinear wave field had not arrived at the rivet holes yet.

Figure 5c presents the nonlinear wave field energy profile by further integrating the temporal domain signals. The nonlinear energy distribution became very indicative of the fatigue damage. The inherent nonlinearity in the interrogating wave field could be clearly observed. In addition, the nonlinear energy concentrated on the crack tips where strong nonlinear interactions happened. In this way, the fatigue crack was clearly visualized via the nonlinear ultrasonic SLDV technique.

CONCLUDING REMARKS

This paper reported the recent modeling and experimental endeavors on nonlinear ultrasonic guided waves for fatigue crack detection and evaluation in the Active Materials and Intelligent Structures (AMIS) lab at Shanghai Jiao Tong University. The progress on the further development of efficient LISA modeling tool was first presented. Special wave crack interaction features were discussed by considering rough crack surface condition. Subsequently, the experimental investigations were presented. The first experimental research effort strived to incorporate the wave control capability of metamaterials into the nonlinear ultrasonic SHM and NDE procedure. An ultrasonic bandgap meta-surface was demonstrated for the elimination of inherent second harmonic to enhance the sensitivity and reliability of the nonlinear ultrasonic system. The second experimental effort adopted the nonlinear mode conversion and scattering features of guided waves at fatigue cracks for improved imaging of the damage using the Scanning Laser Doppler Vibrometry (SLDV). These research results showed that nonlinear ultrasonic guided waves enabled the effective detection and evaluation of fatigue cracks.

ACKNOWLEDGEMENTS

The support from the National Natural Science Foundation of China (contract number 51605284) is thankfully acknowledged.

REFERENCES

1. D. Dutta, H. Sohn, K. A. Harries and P. Rizzo, "A nonlinear acoustic technique for crack detection in metallic structures," *Strctural Health Monitoring, An International Journal,* vol. 8, no. 3, pp. 251-262, 2009.
2. K. Jhang, "Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review," *International Journal of Materials,* vol. 10, p. 123–135, 2009.
3. 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 - An International Journal,* vol. 11, no. 2, pp. 197-211, 2011.
4. M. Hong, Z. Su, Y. Lu, H. Sohn and X. Qing, "Locating fatigue damage using temporal signal features of nonlinear Lamb waves," *Mechanical Systems and Signal Processing,* vol. 60, p. 182–197, 2015.
5. W. Wu, W. Qu, L. Xiao and D. Inman, "Detection and localization of fatigue crack with nonlinear instantaneous baseline," *Journal of Intelligent Material Systems and Structures,* vol. 27, no. 12, p. 1577–1583, 2016.
6. P. Liu, H. Sohn, T. Kundu and S. Yang, "Noncontact detection of fatigue cracks by laser nonlinear wave modulation spectroscopy (LNWMS)," *NDT&E International,* pp. 106-116, 66 2014.
7. Y. Shen, C.E.S. Cesnik, “Hybrid local FEM/global LISA modeling of damped guided wave propagation in complex composite structures”, *Smart Materials and Structures,* Vol. 25, pp. 1-20, 2017
8. Y. Shen, J. Wang, W. Xu, “Nonlinear features of guided wave scattering from rivet hole nucleated fatigue cracks considering the rough contact surface condition”, *Smart Materials and Structures,* Vol. 27, No. 10, pp 1-15, 2018
9. W. Staszewski, R. Jenal, A. Klepka, M. Szwedo and T. Uhl, "A review of laser doppler vibrometry for structural health monitoring applications," *Key Engineering Materials,* vol. 518, pp. 1-15, 2012.

DEStech Publications, Inc.

CONTRIBUTING AUTHOR COPYRIGHT RELEASE FORM

As author of the chapter/contribution titled Modeling and Experiments on Nonlinear Ultrasonic Guided Waves for Fatigue Crack Detection and Evaluation, to appear in the *Proceedings of Structural Health Monitoring 2019*, I hereby agree to the following:

1. To grant to DEStech Publications, Inc., 439 North Duke Street, Lancaster, PA, 17602, copyright of the above named chapter/contribution (for U.S. Government employees to the extent transferable), in print, electronic, and online formats. However, the undersigned reserve the following:
a. All proprietary rights other than copyright, such as patent rights.
b. The right to use all or part of this article in future works.

DEStech Publications thereby retains full and exclusive right to publish, market, and sell this material in any and all editions, in the English language or otherwise.

1 I warrant to DEStech Publications, Inc., that I am the (an) author of the above-named chapter/contribution and that I am the (a) copyright holder of the above-named chapter/contribution granted to DEStech Publications, Inc.

2 I warrant that, where necessary and required, I have obtained written permission for the use of any and all copyrighted materials used in the above-named chapter/contribution. I understand that I am responsible for all costs of gaining written permission for use of copyrighted materials.

3 I agree to assume full liability to DEStech Publications, Inc. and its licensee, and to hold DEStech Publications, Inc. harmless for any claim or suit filed against DEStech Publications, Inc. for violation of copyrighted material used in the above-named contribution.

Please sign and date this form and retain a copy for your records. Please include original form with your chapter/paper.

Thank you for your cooperation.

Please print name: ________________Yanfeng Shen__________________
Signed: _______ Shen ______Dated: ________May 1st, 2019_____

439 NORTH DUKE STREET • LANCASTER, PENNSYLVANIA 17602-4967, U.S.A. Toll Free: (866) 401-4337 • Tel: (717) 290-1660 • Fax: (717) 509-6100 E-mail: info@destechpub.com • Internet address: www.destechpub.com