COVER SHEET

Title: Health Monitoring of Aerospace Bolted Lap Joints Using Nonlinear Ultrasonic Spectroscopy: Theory and Experiments

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ABSTRACT

This paper presents theoretical and experimental study of nonlinear ultrasonic spectroscopy method for health monitoring of aerospace bolted lap joints. In this study, the interrogating waves generated by a transmitter piezoelectric wafer active sensor (T-PWAS) propagate along the structure, interact with the lap joint contact surfaces, carry the information of bolt preload and are picked up by a receiver PWAS (R-PWAS). The contact acoustic nonlinearity (CAN) introduced by the interaction between guided waves and contact surfaces serves as an index for the assessment of bolt tight/loose status. Contact finite element models (FEM) are built to simulate the contact behavior of the lap joint surfaces under ultrasonic wave cyclic loading. The relationship between bolt preload and the CAN is investigated. Experiments on an aerospace bolted lap joint are carried out to verify the FEM predictions. The nonlinearity from the electronic equipment (function generator, amplifier, etc.) is addressed. Scanning Doppler laser vibrometer is used to visualize the wave propagation and interaction with the lap joint, and the results are compared with FEM simulation. Nonlinear effects such as higher harmonics are observed from the FEM predictions and the experimental results. The paper finishes with conclusions and suggestions for future work.

INTRODUCTION

Bolted lap joints are widely used to connect mechanical components. The loosening of bolt load may result in instant structural failure or progressive high level of fatigue on neighboring fastening areas. Thus, a structural health monitoring (SHM) strategy is desired for bolt tight/loose condition monitoring.

Piezoelectric wafer active sensors (PWAS) are convenient enablers for active structural sensing [1]. They could be permanently bounded on host structures and achieve real time SHM. PWAS transducers can be used as both transmitters and receivers, and can work in multiple modes to interrogate the host structure.

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Many researches have been carried out, aiming at developing SHM techniques for bolt load monitoring using ultrasonic waves. Attenuation based method relates the transmitted wave energy with bolt preload level [2]. Wave propagation delay method relates the relative delay of waves with applied torque [3]. Numerical studies have been done to investigate the wave interaction with bolted lap joints [4, 5]. Nonlinear ultrasonic techniques compared with traditional linear methods are found to be more sensitive to incipient changes with their distinctive sub and higher harmonics and side band effects [6]. However, the nonlinear techniques still leaves many aspects to be understood and investigated before they can be implemented in SHM systems. This paper studies the nonlinear ultrasonic spectroscopy method both theoretically and experimentally for the application of bolted lap joints tight/loose status monitoring.

FINITE ELEMENT MODELING OF WAVE INTERACTION WITH BOLTED LAP JOINTS

To understand how guided waves interact with bolted lap joints, a 3-D multi-physics transient dynamic contact finite element model is built. Commercial ANSYS code is used. Contact acoustic nonlinearity (CAN) is generated by the lapped area local apparent stiffness change. The relationship between CAN and bolt load are analyzed using numerical simulation.

Setup for Contact Finite Element Model

Figure 1 shows the finite element model for studying wave interaction with a bolted lap joint. The structure is made of two 11 inches long, 2 inches wide and 1/16 inch thick aluminum 6061 plates. The lap joint has an overlap of 1 inch, so that the total overlap area is 2 square inches. Two PWAS transducers are placed symmetric to the bolt line. The distance between the two PWAS transducers is 4.75 inches.

PWAS transducers are modeled with coupled field elements (SOLID5) which couple electrical and mechanical properties to simulate piezoelectric material. The contact surfaces are modeled with a contact pair (CONTA174 and TARGE170). The transmitter PWAS (T-PWAS) is excited with Hanning window modulated sine tone burst (36 kHz 20 counts 50 Vpp). The bolt load is applied through the pressure loading on the washer area. The pressure is calculated from Eq (1).

$$P = \frac{T}{kdA} \tag{1}$$

where P is the pressure, T is the applied torque, k represents the torque coefficient which depends on a variety of parameters including but not limited to geometry and friction of the threads, d is the nominal diameter of the bolt, and A is the washer area.

The applied torque is changed from 5 $in \cdot lb$ up to 50 $in \cdot lb$ by a step of 5 $in \cdot lb$ to simulate different situations of bolt load. The ultrasonic waves generated by the T-PWAS propagate along the lap joint, interact with the joint contact surfaces and are picked up by the R-PWAS. The wave signals are recorded, analyzed and then compared with experimental results.

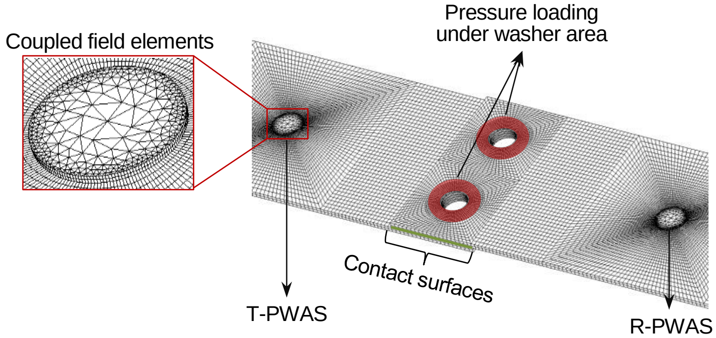

Figure 1: Finite element model of the bolted lap joint

EXPERIMENTAL INVESTIGATION OF NONLINEAR PHENOMENA IN WAVE INTERACTION WITH BOLTED LAP JOINTS

Experiments are carried out to verify the numerical results and further study the nonlinear ultrasonic spectroscopy method in real application. The geometry of the specimen is the same as described in the previous section.

PWAS Pitch-catch Nonlinear Ultrasonic Experimental Setup

The experimental setup for pitch-catch nonlinear ultrasonic experiment is shown in Figure 2. Hanning window modulated sine tone burst signal (36 kHz 20 counts) is generated by the function generator. This signal is then amplified by an amplifier to 50 Vpp and applied to the T-PWAS. The T-PWAS converts the electrical energy into mechanical energy and generates ultrasonic guided waves which interact with the bolted lap joint. The interrogating waves are finally picked up by the R-PWAS, where the mechanical energy is converted back into electrical signal and recorded by the oscilloscope.

Figure 2: Experiment setup 1: pitch-catch active sensing using PWAS

Scanning Doppler laser vibrometer for wave propagation visualization

To visualize the wave propagation in the bolted lap joint structure and compare with FEM predictions, scanning Doppler laser vibrometer is used to capture the propagating wave field. The experimental setup is shown in Figure 3. The excitation signal generated by the function generator and amplifier is applied on the T-PWAS. The scanning Doppler laser vibrometer scans the specimen surface, and measures the out-of-plane vibration velocity during wave propagation. The out-of-plane wave field is then visualized by post processing of the scanning data.

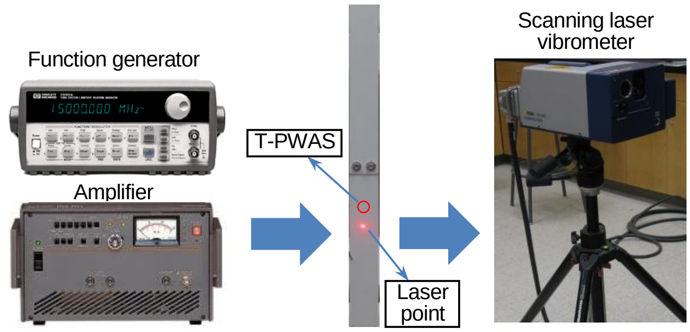

Figure 3: Experiment setup 2: scanning Doppler laser vibrometer for visualizing wave propagation

RESULTS AND DISCUSSIONS

Waveform and Propagating Wave Field

Figure 4 shows the snap shots of simulation results. It could be observed that the washer loading areas are subjected to high level of stress. Guided ultrasonic waves generated by the T-PWAS interact with the lap joint, and the contact surfaces are closed and opened under the cyclic wave excitation. The total area of contact surface changes while the interrogating waves pass through the lap joint. When contact surfaces are closed, the lap joint reacts with the waves like a continuous medium. However, when contact surfaces are partially opened, the non-contact area cannot let the waves pass through, and the lap joint acts as a discontinuous medium. The nonlinearity of the received wave signal lies in the fact that the apparent local stiffness of the lap joint changes under cyclic wave excitation. It is important to note that under higher torque level, the contact surface close and open phenomenon will degrade.

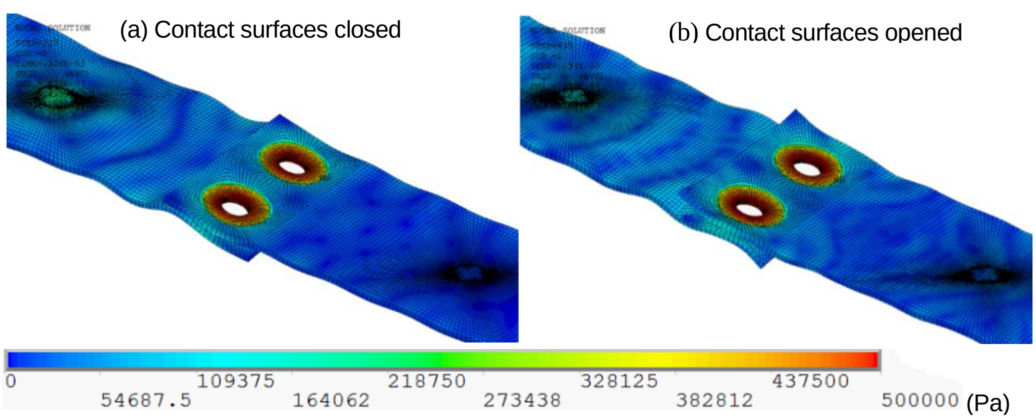

Figure 4: Wave interaction with the lap joint for 10 in-lb loading condition: (a) contact surfaces closed; (b) contact surfaces opened

Figure 5 presents the comparison between simulation and experimental waveforms for torque load of 10 $in \cdot lb$ case. It can be observed the waveforms are in good agreement with each other. It should be noted that the experimental waveform is found to be very sensitive to the lap joint condition. Fine tuning of the plat and bolt placement were used to achieve the results shown in Figure 5. The wave amplitudes of the multi-physics FEM simulation and the experiment differ from each other by a factor around 50. Normalization to the maximum amplitude is used to compare the waveforms from the experiment and simulation.

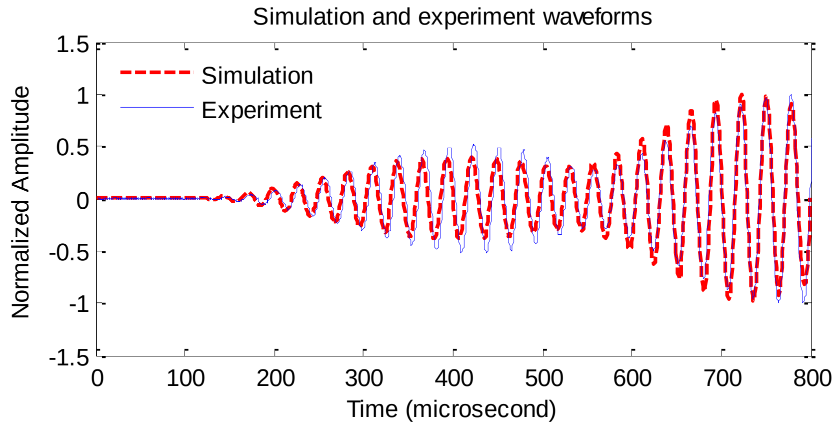

Figure 5: Comparison between simulation and experiment waveforms for 10 in-lb loading condition

The propagating wave fields captured by scanning Doppler laser vibrometer and calculated by finite element simulation are shown and compared in Figure 6.

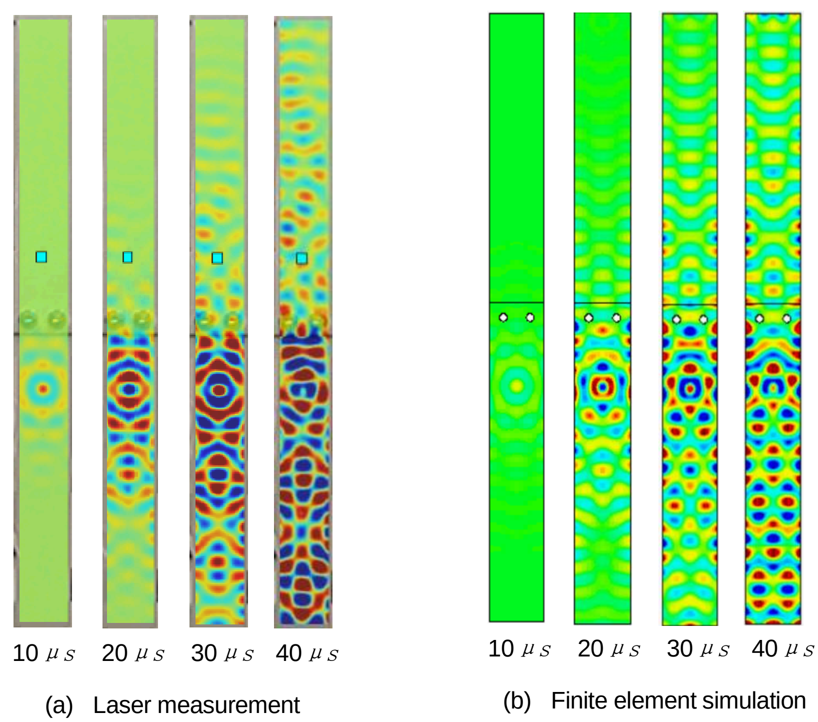

Figure 6: Comparison between wave fields: (a) Laser measurement; (b) Finite element simulation

Figure 6 shows the wave fields captured by scanning laser vibrometer and calculated by FEM. The wave fields at 10 μs clearly display the waves being generated by the T-PWAS, and propagating into the lap joint structure. At 20 μs, the reflections from the edges can be observed, and the interaction between the interrogating waves and the bolted area can be noticed. The wave fields at 30 μs shows the interference between forward propagating waves and reflections from boundaries. The wave fields at 40 μs shows the phenomenon of wave interference and the pattern of local resonance. It should be noted that the finite element simulation represents ideal manufacturing and loading conditions of the bolted lap joint, while the real specimen has machinery manufacturing tolerance and uncertainties in loading conditions. For instance, the numerically calculated wave field is symmetric, but the laser measurement is not, especially after the interaction with the lap joint area. The finite element model is artificially restricted at three different nodes at the end to constrain structural rigid body motion, which will also result in differences between the experimental wave field and the numerical simulation.

Spectral Analysis of Sensing Signals

Figure 7 shows the frequency spectrum of the simulation signal and the experimental data. It can be noticed that beside the fundamental excitation frequency at f_c, distinctive nonlinear higher harmonics at $2f_c$ and $3f_c$ are also present in both simulation signal and experimental data. This shows the contact model can simulate the nonlinear phenomena of wave interaction with the bolted lap joint.

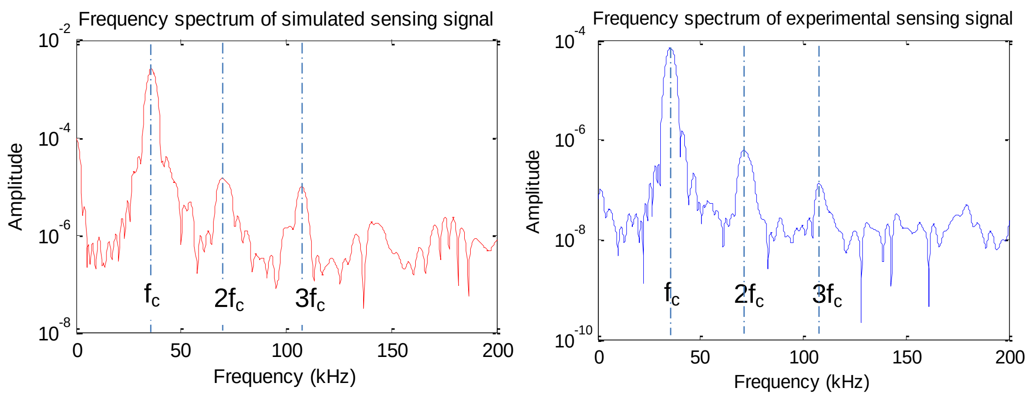

Figure 7: Frequency spectrum of simulation and experimental signal

The degree of nonlinearity is expressed by Eq (2), and serves as the index of tight/loose status of the bolted lap joint.

$$DI = \sqrt{\frac{A(2f_c)}{A(f_c)}} \tag{2}$$

where $A(f_c)$ and $A(2f_c)$ denote the spectral amplitude at the excitation frequency and at the second harmonic. The nonlinearity indexes of various torque values are calculated for both the simulation and five independent sets of experiments.

Figure 8 shows the nonlinearity index results. It could be observed from Figure 8(a) that the numerical simulation result shows a clear decaying trend of nonlinearity with increasing applied torque, which indicates that tighter joint approaches linear system with contact surfaces firmly clamped together. However, the experimental data in Figure 8(b) shows much more complicated pattern. In general, under low applied torque values, the nonlinearity index of the signal is high, and then with increased torque, the index fluctuates around certain values. Statistically, Figure 8(c) shows at low value of applied torque, an increment of nonlinearity index could indicate the loosening of bolts.

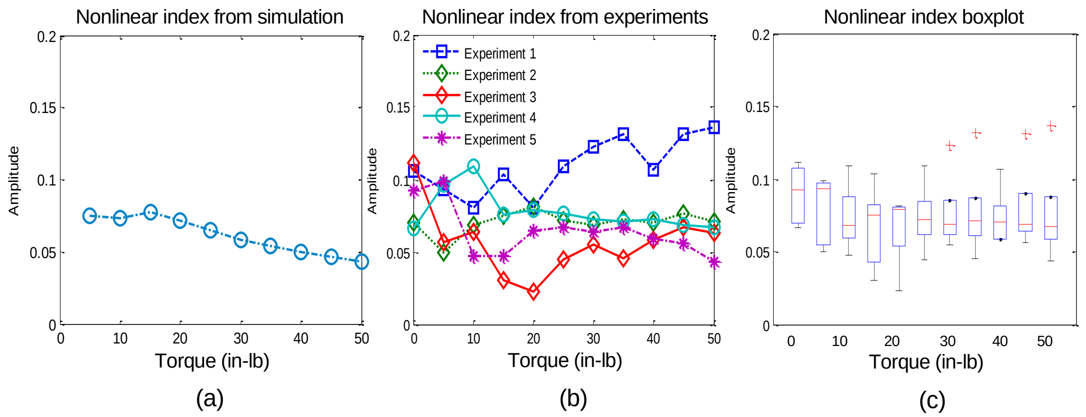

Figure 8: Nonlinear index plots: (a) FEM simulation results; (b) experimental data; (c) statistical boxplot

A possible cause of the complicated nonlinearity index pattern is the inherent nonlinearity from the excitation signal constructed by function generator and amplifier.

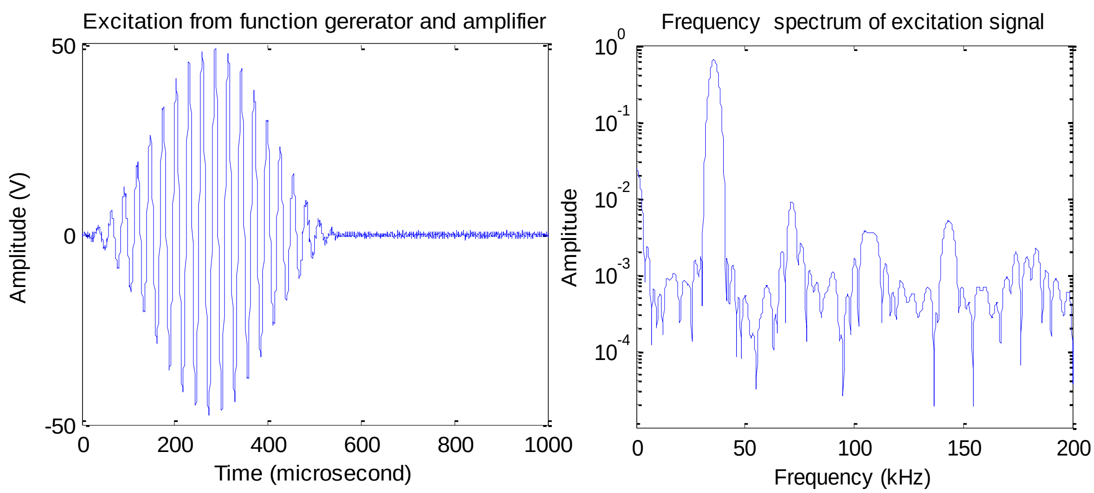

Figure 9: Excitation signal and inherent nonlinearity from electronic equipment

Figure 9 shows the excitation signal constructed by the function generator and amplifier, and directly recorded by the oscilloscope. The frequency spectrum of the excitation signal shows higher harmonic frequency components generated by the electronic equipment, which will influence the experimental results. These inherent higher harmonic frequency components will also be converted by the T-PWAS and contribute to the R-PWAS received signal. It is difficult to distinguish between the inherent nonlinearity from electronic equipment and the nonlinearity from wave-structure interaction. The transmission coefficients for different frequency components may vary with the bolt loading conditions, resulting in the complicated nonlinearity index change patterns.

CONCLUSIONS AND FUTURE WORK

Conclusions

The contact finite element model can describe the interaction between guided ultrasonic waves and bolted lap joints. The waveforms and wave fields from the FEM simulation agree well with the experimental data from PWAS pitch-catch and scanning laser vibrometer measurements. Distinctive nonlinear higher harmonics are found in both the numerical simulation and experimental results. The theoretical study shows a decaying trend of nonlinearity with increasing applied bolt load level, which could be used as a correlating quantity for monitoring bolt tight/loose status. However, the experimental data shows more complicated patterns. Two sources of nonlinearity are found in the experiments: (1) inherent nonlinearity from electronic equipment; (2) nonlinearity from wave-structure interaction. The final nonlinearity has the contribution from both sources.

Future Work

The possibility of separating inherent nonlinearity and wave-structure interaction nonlinearity should be explored. For instance, the frequency components at higher harmonics may be tuned out using PWAS tuning effect. Design of test specimen should be improved to represent the real structures, for example, two plates joint by multiple bolts or rivets. The case of loosening only one of the multiple bolts should also be explored by this nonlinear spectroscopy method using PWAS transducers.

ACKNOWLEDGEMENT

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