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Simulation Based Optimization of Sensor Network for SHM of Complex Structures

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Abstract

In this paper, we present simulation schemes and results to aid in optimizing the sensor placement location in a PWAS sensor network for monitoring growth of crack from rivet line in complex stiffened structures. The crack growth-monitoring scheme is discussed. An example is shown where the sensor network detects location and size of cracks from a probable region of rivet line in a stiffened skin of aircraft. The design approach is such that the Sensor network optimization is achieved with minimal network hardware footprint for maximal area of coverage. A guided ultrasonic wave based sensor system operating in pulse-echo mode is simulated to detect growth of crack from rivet line to illustrate the design approach developed.

1 INTRODUCTION

Condition based monitoring (CBM) using integrated piezo transducers in aircraft structures have emerged as viable solutions in Integrated Vehicle Health Monitoring (IVHM) under the broad framework of Structural Health Monitoring (SHM). Near-field sensing based on strain and vibro-acoustic signature is one type of monitoring in complex structural components involving joints, mounts, landing gear, engine components etc. Far-field sensing based on ultrasonic guided wave is another type of monitoring involving larger size complex structures like stiffened structural components, where a network of PWAS transducers are considered suitable.

One of the commonly used non-destructive methods for damage interrogation is the ultrasonic inspection technique. The ability to resolve small damages in inaccessible regions of a component makes it a popular interrogation method. Ultrasonic guided wave technique using Piezo-electric using piezo-electric wafer active sensors (PWAS) has grown into an effective method in damage detection in structures [1]. However, the complex interference patterns produced due to the interaction of the wave with various geometric features in the component makes the detection process complex. In plate or shell like structures, guided waves can be used to monitor damages and material property changes, and applications of such have been reported in literature.

Sensor network optimization with minimal network hardware footprint and maximal area of coverage remains a challenging problem. PWAS sensors are placed at discrete locations in order to inspect damages in stiffened structures and such design of SHM system has the potential to be extended to assembled structures. Various actuator-sensor configurations are possible within the network in order to identify and locate damages.

One of most important damages required to be inspected carefully in assembled structures are rivet-hole cracks [2]. The damage identification is done by monitoring the waves reflected or transmitted through the damages. This calls for placing sensors at multiple locations on the component for effective monitoring of the damage. The drawback however is two-fold. The placement of sensors are done based on the design criteria and loads acting on the component since there is no prior knowledge on how and where a crack like damage will initiate and propagate. The second is that the inspection method requires employing complex signal processing algorithms to analyze the data [3, 4, 5] at various sensors. This process can be simplified by use of simulation where wave-field and its interactions with other structural features can be modelled and detection algorithms can be designed for effective monitoring.

In this paper, we present an approach to monitor cracks emanating from rivet line using ultrasonic guided wave signal from the PWAS sensor network. The effect of crack growth on amplitude of signal is discussed. The effect of damage growth on phase of the signal have already been discussed by the authors [6]. A specific example of crack growing on stiffened skin of an aircraft is taken and simulations are performed the study the effect of growth on the crack size is discussed in this paper.

2 COMPONENT GEOMETRY AND SIMULATION PROCEDURE

For the simulation, we considered an example of stiffened skin of an aircraft made of 2mm thick aluminium with a rivet line pitch ‘P’ of 30mm as shown in Fig 1. We assume a fatigue crack from one of the rivet holes, where the crack length is a parameter to be estimated. For condition based monitoring (CBM) in flight in an integrated manner, the sensor network needs to be placed permanently according to the geometric features of the component and the likelihood of damage from such features. Suitable algorithm for damage detection and monitoring of damage growth needs to be developed. However, these algorithm could be specific to the component and the location of the sensor and need not be generic. These algorithms can be validated and optimized to a great extent with the help of simulations. In this paper, we consider a scenario where Piezoelectric wafer active sensors (PWAS) are assumed to be have been bonded to the riveted panel thereby forming a part of PWAS sensor network. Consider locations P1 and P2 along the rivet line to monitor any rivet line damage as shown in the Fig 1. We assume that the sensors are operating in pulse-echo mode. The following simulation based approach presents a methodology to monitor damage assuming sensors located at locations P1 and P2. This could then be mapped to a scenario where damage is monitored in real time.

The ability to detect the smallest defects within a material domain depends upon the wavelength of the incident wave, wave propagation characteristics, noise and uncertainty in various quantities involved. Simulation presents a useful way to analyze how the wave path is influenced by the damages and other structural features. A spectral finite-element based modelling scheme is used to analytically evaluate the displacement fields at any given point in the component and model the propagation of Lamb wave within the component. When an excitation signal is given to the sensors, a circular wave-front is created. The wave front propagates and interacts with the structural features on the component, where in this case the structural features are the crack and the holes in the plate. Each sensor therefore receives a component of the wave from every such reflection, assuming that the reflections reach the sensor within the inspection window.

The inspection window (time signal packet length) is set such that the reflections received are limited to the nearest three rivet holes. If the sensor is located along one of the rivet line as indicated by P1 in Fig 1a, we denote the distance between the sensor and rivet along the same line as L and distance between sensor and the nearest two holes as D. When there is no crack, the sensor would be receiving the component of wave reflected from the three rivet holes. When a damage is present as shown in Fig 1(b), a phase shift and amplitude change occurs due to path difference between the holes and the crack. A cross-correlation based technique was developed to identify the phase shift that is introduced due to the crack from the rivet hole [6].

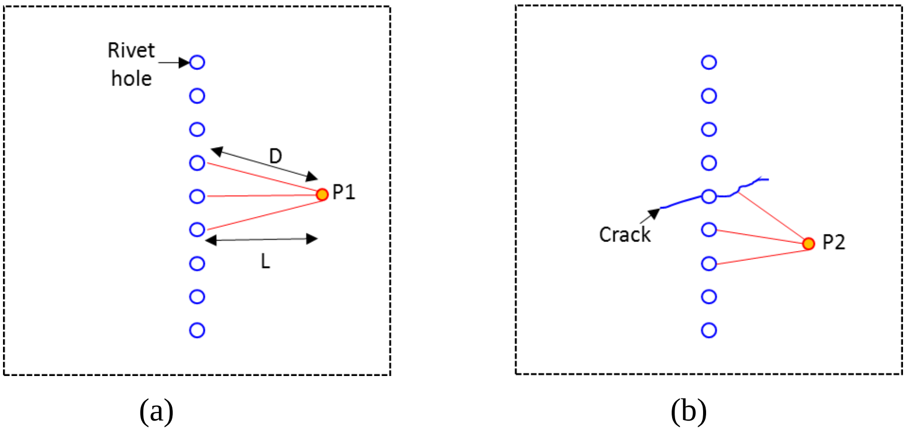


Fig 1. (a) Placement of sensor with respect to rivet hole, (b) a phase shift occurs due to path difference caused due to presence of crack

3 QUANTITATIVE INDEX TO MONITOR CRACK GROWTH

We define a correlation function J which is an algebraic sum of the auto-correlation and the cross cross-relation of the two signals defined by the following equation

$$J(t) = u(t) * u(t) - u(t) * v(t) \tag{1}$$

Where '*' defines a correlation operation between reference signal u(t) and signal due to damage v(t). The reference signal could be signal when damage was absent or from a previously cracked condition from which a crack size increment is estimated progressively. Therefore, in frequency domain,

$$J(\omega) = |U(w)|^2 - \hat{U}(\omega)V(\omega) \tag{2}$$

Where '^' denotes the complex conjugate.

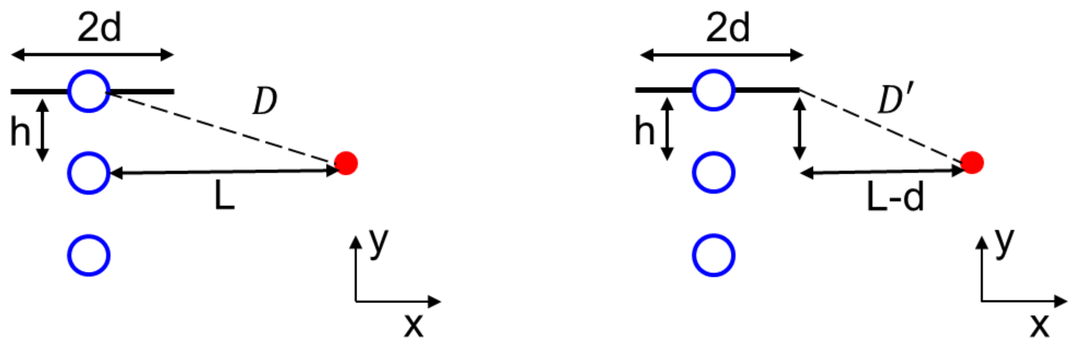
The phase change in signal neglecting amplitude variation due to crack was determined [6] as

$$\phi = 2\tan^{-1}\left(\frac{\int_{-\infty}^{\infty}|U(\omega)|^2\cos(\omega t)\,d\omega}{\int_{-\infty}^{\infty}|U(\omega)|^2\sin(\omega t)\,d\omega}\right) \tag{3}$$

To consider the effect of amplitude variations on the correlation function, the reflected wave at the sensor location can be represented as

$$V(\omega) \cong V_o(\omega)\sqrt{\frac{r}{r_o}} \tag{4}$$

where V_o (ω) is the transmitted wave amplitude and the other term is the cylindrical loss due to propagation where r is the radius of the transducer and r_o is the total distance traversed by the wave.



(a) (b)

Fig 2 Schematic showing the dimensions of the sensor with respect to the rivet holes

Consider a situation where the piezo is located in line with one of the rivet holes. As the crack size increases, there is an increased reflection from the surface of the crack. Therefore, by simple geometry from Fig 2, the distance between the crack tip and the piezo is given by

$$D' = \sqrt{h^2 + (L-D)^2} \tag{5}$$

In case of reflections from crack, (5) can be substituted in (4) for r_o and the ratio of the transmitted and reflected amplitudes is therefore given by,

$$\frac{V_0(\omega)}{V(\omega)} = \sqrt{\frac{2\sqrt{h^2+(L-D)^2}}{r}} \tag{6}$$

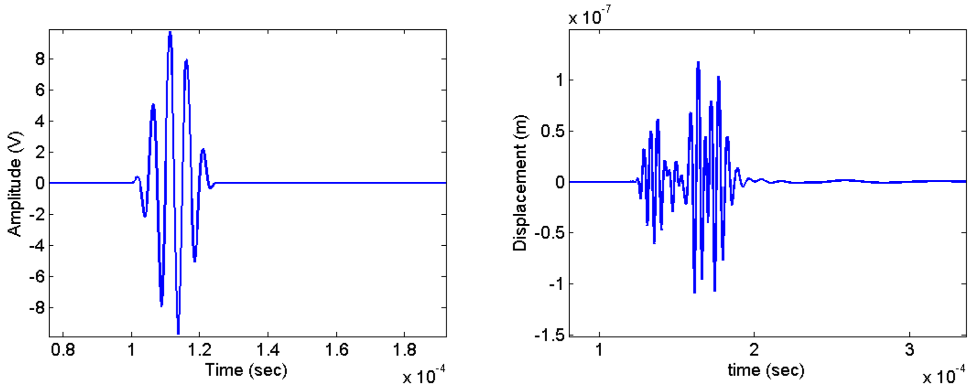
Substituting Eqn. (6) in Eqn. (2), the effect increasing crack size is on the correlation output is determined. The scheme can be used further to estimate the crack size as well.

A methodology discussed in [7] was used to reconstruct the signal at sensor location. The modelling scheme involves numerically evaluating the displacement fields and coupling with scattering models near the holes and crack. An appropriate transducer transfer function is then used to convert the excitation signal in terms of strain and vice-versa.

4 RESULT S AND DISCUSSION

The signal was simulated with a 200 KHz, 5 cycle amplitude modulated wave for a 2mm thick Aluminium plate. To model the signal, analytical functions were used to convert the actuator signal into displacement field, and appropriate scattering models were used at crack locations and hole along with cylindrical losses. This is one of the major criteria for amplitude changes in the signal. The signal was then reconstructed at the sensor location using receiver transfer function to convert displacement field to voltage. All the signals over the sequence of scan were normalized for comparison. We consider a time window of interest from the sensor such that only reflections from the three nearest holes were considered to analyze the reflections from hole and crack.

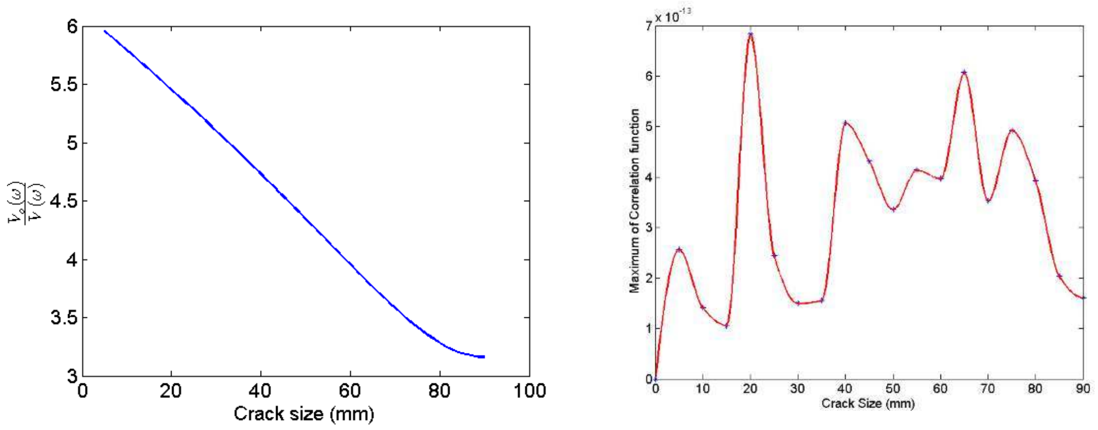
The simulations were performed for crack sizes up to 90mm and signal with no crack is assumed to be the healthy signal. This was used as reference signal when the correlation function was calculated.



(a) (b)

Fig 3 (a) 200 KHz, 5 cycle Amplitude Modulated Excitation Signal, (b) Reconstructed signal at sensor for a crack size of 90mm

Fig 3 shows the reconstructed signal when the crack size was 90 mm. The correlation function was evaluated to determine the correlation index for signal simulated over increasing crack size and correlation index with respect to the crack size is plotted in Fig 4(b). The correlation index variation plotted at sensor location P1, shows the sensitivity of amplitude changes to increasing crack size. A similar kind of correlation plot can be generated for different sensors in the network to study the sensitivity of the sensor to pick up changes in the structural features on the component. The correlation function can then be evaluated for real-time signals from sensor which can then be used with the simulation data to monitor the crack growth. The simulation process therefore helps to identify and optimize the sensor network such that every sensor can work independently with minimal network hardware, but at the same time, is sensitive to any change in structural features on the test component.



(a) (b)

Fig 4 (a) Amplitude ratio variation with respect to crack size, (b) Correlation function output for increasing crack size

5 CONCLUSIONS

We presented a simulation based approach to monitor crack growth from rivet line using ultrasonic guided wave signal on an example stiffened skin of an aircraft using sensors that is mounted on the surface of the skin. We then introduced a correlation function to determine a correlation and its variation over increasing crack size. We then show data obtained through simulation can be fused with real-time data to monitor damage growth. The design approach taken is to optimize the sensor network such that there is an increase coverage with minimal hardware foot print.

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