AFRL-ML-WP-TP-2006-458

SIMULATION-BASED DESIGN OF A GUIDED-WAVE STRUCTURAL HEALTH MONITORING SYSTEM FOR A PLATE-STIFFENER CONFIGURATION

J.C. Aldrin, E.A. Medina, K.V. Jata, and J.S. Knopp

AUGUST 2006

Approved for public release; distribution is unlimited.

STINFO COPY

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YY)***
August 2006

2. REPORT TYPE
Conference Paper Postprint

3. DATES COVERED ***(From - To)***

4. TITLE AND SUBTITLE
SIMULATION-BASED DESIGN OF A GUIDED-WAVE STRUCTURAL HEALTH MONITORING SYSTEM FOR A PLATE-STIFFENER CONFIGURATION

5a. CONTRACT NUMBER
F33615-03-D-5204

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102S

6. AUTHOR(S)
J.C. Aldrin (Computational Tools, Inc.)
E.A. Medina (Enrique Medina & Associates)
K.V. Jata and J.S. Knopp (AFRL/MLLP)

5d. PROJECT NUMBER
4349

5e. TASK NUMBER
41

5f. WORK UNIT NUMBER
05

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Computational Tools, Inc.
4275 Chatham Avenue
Gurnee, IL 60031

Enrique Medina & Associates
P.O. Box 340646
Dayton, OH 45430

Nondestructive Evaluation Branch (AFRL/MLLP)
Metals, Ceramics and NDE Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2006-458

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Published in Structural Health Monitoring 2006: Proceedings of the Third European Workshop (2006, pp. 1078 – 1085), DES*tech* Publications, Inc.

This work was funded in whole or in part from Department of the Air Force contract number F33615-03-D-5204.

14. ABSTRACT
Through the use of integrated sensing and signal processing for damage detection, structural health monitoring (SHM) technologies are expected to improve system life cycle management. In particular, guided waves have been successfully utilized for damage identification in pipes and other structures. However, the design of guided wave applications becomes significantly more challenging as the geometric complexity of the structure increases. Structural components for aircraft wings, container tanks, and other applications often have one or more substructures that consist of plates with stiffeners. The application of both higher frequency Rayleigh waves and lower frequency Lamb waves were considered for the inspection of a plate-stiffener configuration for fatigue cracks, with each providing advantages and challenges for practical application. The finite element method was used to better understand both mode conversion and scattering characteristics associated with the crack relative to the rib joint geometry. The multi-objective optimization scheme coupled with a parametric numerical model is lastly discussed for SHM design optimization in terms of maximizing the sensitivity of signal processing measures to crack length while minimizing the significance of secondary signals due to the part geometry and a varying material state.

15. SUBJECT TERMS
Structural health monitoring, guided waves, signal processing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kumar Jata
Unclassified	Unclassified	Unclassified	SAR	14	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Simulation-Based Design of a Guided-Wave Structural Health Monitoring System for a Plate-Stiffener Configuration

J. C. ALDRIN, E. A. MEDINA, K. V. JATA and J. S. KNOPP

ABSTRACT

Through the use of integrated sensing and signal processing for damage detection, structural health monitoring (SHM) technologies are expected to improve system life cycle management. In particular, guided waves have been successfully utilized for damage identification in pipes and other structures. However, the design of guided-wave applications becomes significantly more challenging as the geometric complexity of the structure increases. Structural components for aircraft wings, container tanks, and other applications often have one or more substructures that consist of plates with stiffeners. The application of both higher frequency Rayleigh waves and lower frequency Lamb waves were considered for the inspection of a plate-stiffener configuration for fatigue cracks, with each providing advantages and challenges for practical application. The finite element method was used to better understand both mode conversion and scattering characteristics associated with the crack relative to the rib joint geometry. The multi-objective optimization scheme coupled with a parametric numerical model is lastly discussed for SHM design optimization in terms of maximizing the sensitivity of signal processing measures to crack length while minimizing the significance of secondary signals due to the part geometry and a varying material state.

INTRODUCTION

Structural health monitoring (SHM) technologies are expected to improve system life cycle management of aircraft structures through a condition-based maintenance (CBM) approach. Benefits include increased fleet availability, improved system reliability as components approach failure, and lower sustainment cost due to reductions in structural teardowns and inspection labor. Ultrasonic guided wave methods incorporating in-situ sensors have a significant potential to interrogate a wide

John C. Aldrin, Computational Tools, 4275 Chatham Ave., Gurnee, IL 60031, USA.
Enrique A. Medina, Enrique Medina & Associates, P.O. Box 340646, Dayton, OH 45430, USA.
Kumar V. Jata, Jeremy S. Knopp, Air Force Research Laboratory, Materials and Manufacturing Directorate, 2230 10th Street, Wright-Patterson AFB, OH 45433, USA.

Reprinted from *3rd European Structural Health Monitoring 2006*

area of a structure. Recently, guided wave applications have been successfully implemented for the inspection of pipes. Issues of transducer design and interpreting complex signals have been addressed through the development of analytical and numerical models and novel signal processing methods for array data [1-3].

Many practical considerations exist for the application of ultrasonic methods using in-situ sensors for aircraft SHM. Key challenges include distinguishing crack signals from noise, addressing optimal placement of sensors for observability of expected damage states, ensuring and validating the reliability of sensors over life, and demonstrating an economic benefit for implementation. Recently for aircraft structure applications, research efforts have begun to address novel sensor array designs [4,5], self-calibrating approaches [6], in-situ sensor durability assessment and system certification requirements [7]. However, there is still the significant challenge to quantify the damage state of a structure, distinguishing mission critical defects such as fatigue cracks, delaminations or severe impact damage from coherent noise features present in distributed sensor signals associated with the geometric complexity of the structure. Potential sources for structural noise features include fastener sites, stiffener ribs and risers, lap joints, and attached subsurface structures. In addition, time-driven variations in the structural contact conditions at joints and fastener sites or changes in the sealant properties will also change the dynamics of wave propagation within a structure. Many in-situ SHM approaches are also sensitive to changes in the dynamic, thermal, and mass loading of the structures, which can be considerable during flight or at different bases around the world.

The objective of this paper is to present a case study introducing one level of part geometric complexity, the presence of stiffener ribs in panels, to demonstrate a model-assisted design process. The use of stiffening ribs in structures can be found in a variety of forms for many applications (Figure 1). Extruded panels with ribs are common in many aircraft wing structures. Isogrid panels used for some space structure applications such as the Saturn V rocket are made by machining a triangular pattern of ribs and spaces of reduced panel thickness that provide a good compromise between strength and weight [8]. Under poor processing conditions, the panel sections between ribs may also vary in thickness as shown in Figure 1(b), providing a unique challenge for guided wave methods. Quite often, ribs may be welded to a panel in the form of a T-joint as shown in Figure 1(c). Some experimental and simulated studies have been performed exploring the application of Lamb waves [9,10] and SH waves [11] for the inspection of cracking at a welded rib. Lastly, some bonded joints such as the T-peel joints also exhibit this characteristic geometry as shown in Figure 1(d). Prior work has studied the application of lamb waves to evaluate the bond quality at such joints [12]. The common factor for each stiffened plate geometry from the perspective of ultrasonic scattering is the presence of (1) a fillet (or weld of irregular morphology) and (2) the top of the rib that scatter the incident ultrasonic wave and thus hinder the interpretation of (3) signals associated with cracks located at this joint.

Both higher frequency Rayleigh waves and lower frequency Lamb waves are considered here for the inspection of a plate-stiffener configuration for fatigue cracks, with each providing some promise and challenges for practical application. For cases where the critical locations for flaw growth are well known and few in number, the application of high frequency ultrasonic techniques may be considered. The usefulness of angled beam shear wave, shear horizontal wave (using EMAT

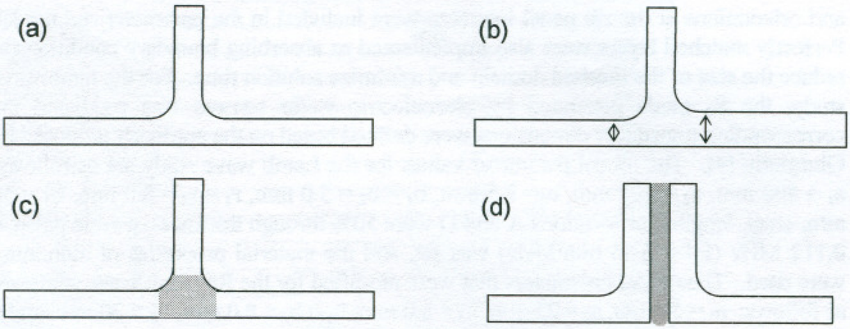

Figure 1. Plate-stiffener structures: (a) extruded panel with rib, (b) machined panel with varying thickness, (c) welded T joint, and (d) bonded composite T-peel joint.

transducers), or Rayleigh wave techniques will depend on the nature of the crack location and orientation. In this study, Rayleigh waves are first considered given their capability to propagate past a joint both along the curved fillet into the rib and leak as a creeping wave into the joint and adjacent panel section. Prior work has studied both the propagation of Rayleigh waves on curved surfaces [13] and the scattering of Rayleigh waves from a sharp 270° corner [14], but little work has been performed on the problem of scattering from 270° corners with curvature beyond recent studies of Lamb wave scattering at pipe bends [15]. Lamb waves are typically used at low frequencies to isolate the propagating modes to the fundamental symmetric (S_0) and asymmetric (A_0) modes and thus simplify the signal interpretation problem. In-situ sensor configurations have been presented for generating S_0 [4] and A_0 [5] modes for interrogating an aircraft structure. Greve el al. recently presented a numerical simulation of Lamb wave scattering in a plate girder geometry containing a crack in a convex weld geometry [10]. In this study, the S_0 mode lamb wave source propagated from the web into the flange and welded region with direct incidence on the crack. Related numerical studies have been performed evaluating mode conversion and the scattering of guided waves from discontinuities in a plate including cylindrical voids (representing corrosion) [16, 5], cracks and notches (recent) [17], steps in the plate (such as at a lap joint), and the interface at overlapping panels [18]. However, gaps still exist concerning a full understanding of the effect of changes in component geometry (plate and rib thickness and height), transducer characteristics (frequency, shape, loading profile), and signal processing parameters on the reliability to detect cracks of various sizes and locations. To build on prior work, this study presents the application a numerical models for rib-stiffener-crack configuration and briefly discusses integration with multi-objective optimization methods for robust design.

NUMERICAL MODEL

Figure 2 presents a diagram of a plate-stiffener configuration with an in-situ transducer. The FEM package, FEAP, was used to solve the 2D explicit finite element problem [19]. Integration with Matlab was facilitated using FEAPMEX to enable full model parameterization and facilitate optimization studies. Several crack locations and orientations at the rib panel interface were included in the parameterized model. Perfectly matched layers were also implemented as absorbing boundary conditions to reduce the size of the meshed domain and minimize solution time. For the lamb wave study, the S_0 mode generated by piezoelectric wafer sensors was used and the corresponding transducer dimensions were defined based on the approach proposed by Giurgiutiu [4]. The model parameter values for the Lamb wave study are as follows: $a_1 = 800$ mm, $a_2 = 400$ mm, $a_3 = 7.5$ mm, $b_1 = b_2 = 5.0$ mm, $r_1 = r_2 = 8.0$ mm, $b_3 = 50$ mm, crack lengths for locations A and D were 50% through thickness, a wide pulse at 0.112 MHz (f·d = 0.56 mm·MHz) was set, and the material properties of aluminum were used. The model parameters that were modified for the Rayleigh wave study are as follows: $a_1 = 50$ mm, $a_2 = 25$ mm, $a_3 = 8.0$ mm, $b_1 = b_2 = 8.0$ mm, $b_3 = 20$ mm, and a short pulse at 1.5 MHz. A mesh criterion of a minimum of six elements was used across a distance associated with the shortest wavelength (mode) present. The explicit time step criteria was thus based on the wave speed associated with the shortest distance between two adjacent nodes in the model.

SIMULATED STUDIES OF THE SCATTERING OF S_0 MODE LAMB WAVE

Simulated studies were initially performed for an incident S_0 mode lamb wave to evaluate the magnitude of the reflected and transmitted modes from an unflawed rib. Figures 3(a) and (b) present the displacement response on the top surface in the y-direction and x-direction respectively (with the rib position identified by a dotted lines in the center) for a series of time steps. Although the x-direction displacement will more readily translate to the measurement response, the presentation of both components provides greater insight into the mode conversion and scattering that occurs at the rib. A strong S_0 mode and a weaker A_0 mode are first observed propagating toward the rib. After the S_0 mode reaches the rib, reflection and transmission of the S_0 mode and mode conversion to reflected and transmitted A_0 modes are observed. Interestingly, the reflected and transmitted signals are comparable in magnitude for both the S_0 and A_0 modes. There is very little measurable response associated with the weaker incident A_0 lamb wave. Additionally,

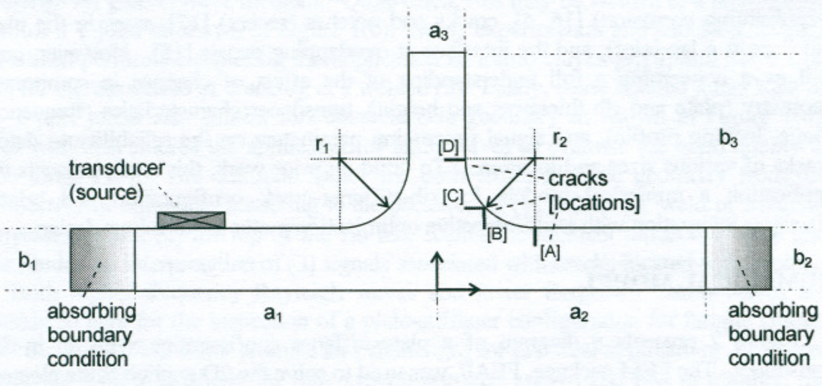

Figure 2. Diagram of a plate-stiffener configuration with a in-situ transducer and multiple locations for cracks.

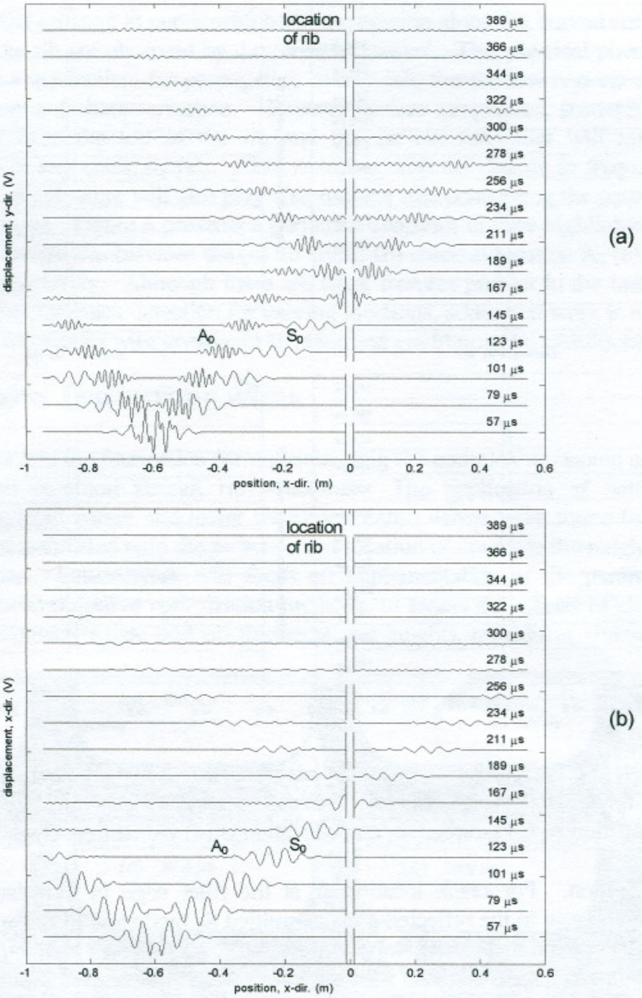

Figure 3. Displacement response in (a) y-direction and (b) x-direction on the top surface of the plate for incident S_0 mode Lamb wave scattered by a rib-stiffener.

greater reverberations are found on the far side of the rib after the initial mode-converted A_0 mode signal, indicating mode conversion, transmission and re-radiation of A_0 lamb waves from the vertical rib. The mode conversion phenomenon has also been observed for other discontinuities in the plate [18–21]; however, the magnitude of the scattered signals from a rib are quantitatively different.

Although subtracting baseline data from suspected crack data may not be practical due to structural and environmental variations producing false indications, a difference based method is presented here to solely demonstrate the differences in the scattered response from a rib for various crack configurations. Figure 4 presents the changes in displacement for the with-crack case A and D (see Figure 2) for both the x-direction

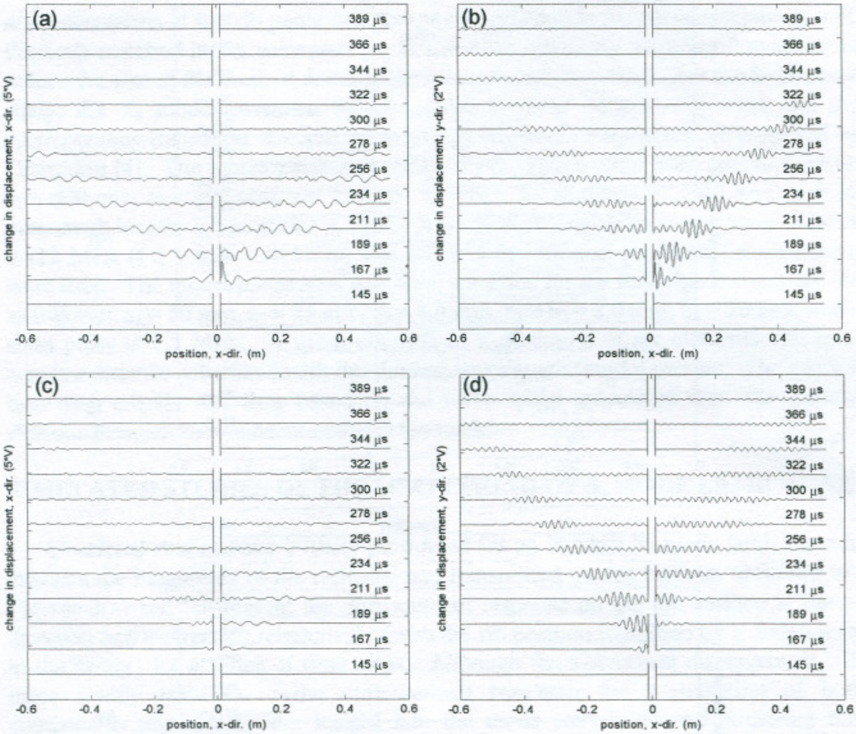

Figure 4. Difference in displacement response between with-crack and no-crack results for the following cases (a) x-direction, crack location A, (b) y-direction, crack location A, (c) x-direction, crack location D (d) y-direction, crack location D.

and y-direction. For crack location A at the fillet edge in the plate, there is a significant change in the reflected and transmitted S_0 mode and likewise the A_0 mode converted from the incident S_0 wave. Alternatively, for crack location D in the rib, there are little change associated with the reflected and transmitted S_0, but most of the changes are associated with mode conversion of A_0 Lamb waves that propagate into and re-radiate from the rib. These preliminary studies provide insight into the potential to characterize flaw location based on the scattered field.

SIMULATED STUDIES OF THE SCATTERING OF RAYLEIGH WAVE

Simulated studies were also performed exploring the scattering of higher frequency Rayleigh waves from the rib geometry. Figure 5 presents contour plots of the RMS displacement response for a series of select time steps. First, as the Rayleigh wave approaches the fillet, interaction of the top surface wave with the bottom plate surface begins. Note at higher frequencies, it is easier to consider the scattering problem as reflections of wavefronts at boundaries as opposed to the superposition of a large number of Lamb wave modes (at f·d = 12 mm·MHz). As the surface wave reaches the fillet (change in curvature), both propagation along the curved surface and leaking into the rib are observed by the 'creeping wave'. This physical phenomenon also provides a mechanism for propagating energy into the shadow regions of rib for crack detection and characterization. However as time progresses, scattered signals are observed from the top of the rib and the far rib fillet that will hinder the interpretation of any crack signals. Also, note that with the change in frequency, rib height and fillet curvature will also play a significant role concerning the nature of the scattered response. Figure 6 presents a particular snapshot in time highlighting some of the subtle differences between the (a) no crack, (b) crack at location A, (c) crack at location D respectively. Although there are weak features present in the images that provide promise for crack detection for varying locations, additional work is needed to best extract such signals with invariance to noise and environmental conditions.

CONCLUSIONS AND FUTURE WORK

This study has laid the foundation for understanding the complex ultrasonic scattering response from common aircraft rib structures. The application of both higher frequency Rayleigh waves and lower frequency Lamb waves were found to provide subtle features associated with the presence and location of cracks in the neighborhood of rib-stiffeners. Future work will focus on implementation of the parameterized model with multi-objective optimization methods, to assess the effects of changes in component geometry (plate and rib thickness and height), transducer characteristics

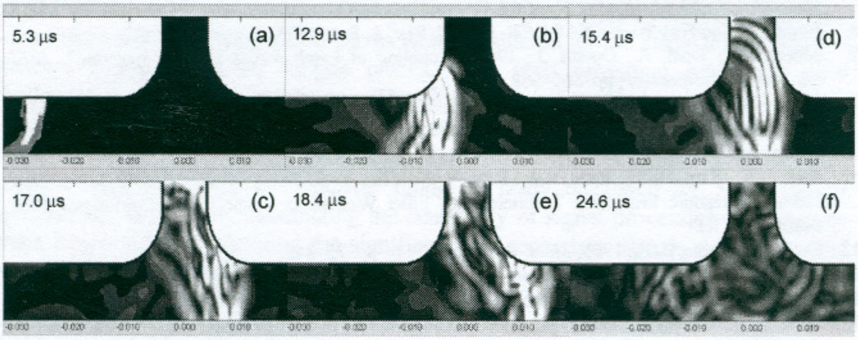

Figure 5. RMS displacement response for an incident Rayleigh wave scattered at a vertical rib for a series of select time steps.

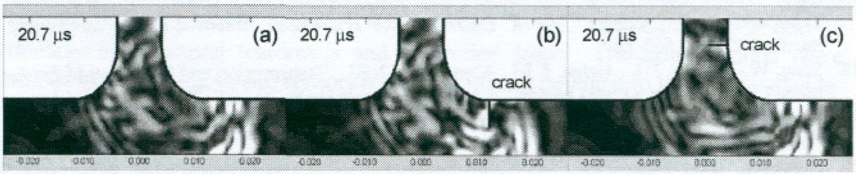

Figure 6. RMS displacement response for an incident Rayleigh wave scattered at a vertical rib with (a) no crack, (b) crack at location A, (c) crack at location D (in the rib) for a select time highlighting differences in the scattered waves.

(frequency, shape, loading profile), environmental state (temperature, residual stress) and signal processing parameters on the ability to detect damage of various sizes at several locations in the structure. Prior work has explored optimization for sensor design and placement for structural health monitoring applications [20]. The multi-objective optimization problem will be defined to maximize the sensitivity of signal processing measures to crack length while minimizing the significance of secondary signals associated with the part geometry.

REFERENCES

1. Rose, J. L., 2002, *Materials Evaluation*, 60(1), pp. 53–59.
2. Cawley, P., 2003, "Practical long range guided wave inspection – managing complexity," *Review of Progress in QNDE*, Vol. 22, pp. 66–75.
3. Cawley, P., Simonetti, F., 2005, "Structural Health Monitoring Using Guided Waves—Potential and Challenges," *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, CA, pp. 503–510.
4. Giurgiutiu, V., 2003, "Lamb Wave Generation with Piezoelectric Wafer Active Sensors for Structural Health Monitoring," Proceedings of SPIE Smart Materials and Structures, San Diego.
5. Fromme, P., Wilcox, P.D., Lowe, M., Cawley, P., 2005, "A Guided Ultrasonic Wave Array for Structural Health Monitoring," *Review of Progress in QNDE*, Vol. 24, pp. 1780–1787.
6. Michaels, J. E., Michaels, T. E., Mi, B., Cobb, A.C., Stobbe, D. M., 2005, "Self-calibrating Ultrasonic Methods for In-situ Monitoring of Fatigue Crack Progression," *Review of Progress in QNDE*, Vol. 24, pp. 1765–1772.
7. Kessler, S.S., Amaratunga, K., Wardle, B.L., 2005, "An Assessment of Durability Requirements for Aircraft Structural Health Monitoring Sensors," *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, CA, pp. 812–819.
8. Isogrid Design Handbook - NASA CR-124075, Rev. A, Feb. 1973.
9. Morvan, B., Tinel, A., Duclos, J., 1999, "Coupling of Lamb waves at a tee junction," *IEEE Ultrasonics Symposium* , pp. 565–568.
10. Greve, D.W., Tyson, N.L., Oppenheim, I.J., 2005, "Interaction of defects with Lamb waves in complex geometries," IEEE Ultrasonics, Ferroelectrics, and Frequency Control Conference, (Rotterdam, September 2005).
11. Park, I.-K., Kim, H.-M., Park, T.-S., Kim, Y.-K., Cho, Y.-S., Song, W.-J., Ann, K., 2005, "Non-contact Ultrasonic Inspection Technology of Fillet Weldments," ASNT Fall Conference 2005, Columbus, OH.
12. Bork, U., Challis, R. E., 1995, *Meas. Sci. Technol.*, 6, pp. 72–84.
13. Viktorov, I., 1967, *Rayleigh and Lamb Waves*, (New York: Plenum).
14. Gautesen, A. K., 2002, "*Wave Motion*, 35, pp. 99–106.
15. Demma, A., Cawley, P., Lowe, M., 2002, "Guided Waves in Curved Pipes," *Review of Progress in QNDE*, Vol. 21, pp. 157–164.
16. Diligent, O., Lowe, M.J.S., Cawley, P., Wilcox, P., 2003, "Reflection of the S_0 Lamb Mode from a Part-Depth Circular Defect in a Plate when the Incident wave is Created by a Small Source," *Review of Progress in QNDE*, Vol. 22, pp. 197–204.
17. Greve, D.W., Tyson, N.L., Oppenheim, I.J., 2005, "Design and Testing of Lamb Wave Transducers," *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, CA, pp. 662–669.
18. Song, W.-J., Rose, J. L., Galan, J. M., Abascal, R., 2003, "Transmission and Reflection of the A_0 Mode Lamb Wave in a Plate Overlap," *Review of Progress in QNDE*, Vol. 22, pp. 1088–1094.
19. Taylor, R. L., *FEAP - A Finite Element Analysis Program, Theory Manual*, University of California, Berkeley, http://www.ce.berkeley.edu/~rlt.
20. Guratzsch, R.F., Mahadevan, S., "SHM Sensor Placement Optimization under Uncertainty," *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Stanford, CA, pp. 662–669.