Fatigue crack growth monitoring in multi-layered structures using guided ultrasonic waves

E Kostson and P Fromme
Department of Mechanical Engineering, University College London, WC1E 7JE, UK
e-mail: e_kostson@meng.ucl.ac.uk; p.fromme@ucl.ac.uk

Abstract. This contribution investigates the application of low frequency guided ultrasonic waves for monitoring fatigue crack growth at fastener holes in the 2nd layer of multi-layered plate structures, a common problem in aerospace industry. The model multi-layered structure investigated consists of two aluminum plate-strips adhesively bonded using a structural paste adhesive. Guided ultrasonic waves were excited using multiple piezoelectric discs bonded to the surface of the multi-layered structure. The wave propagation in the tensile specimen was measured using a laser interferometer and compared to numerical simulations. Thickness and width mode shapes of the excited flexural waves were identified from Semi-Analytical Finite Element (SAFE) calculations. Experiments and 3D Finite Element (FE) simulations show a change in the scattered field around fastener holes caused by a defect in the 2nd layer. The amplitude of the guided ultrasonic wave was monitored during fatigue experiments at a single point. The measured changes in the amplitude of the ultrasonic signal due to fatigue crack growth agree well with FE simulations.

Keywords: Guided Ultrasonic Waves, Fatigue Crack Monitoring, Multi-layered Structure

PACS: 43.35.Zc, 43.35.Cg, 43.35.Yb.

1. Introduction
Ensuring aircraft safety, while controlling costs, is one of the main objectives for aerospace companies. A report from Airbus [1] stresses the fact that there is limited potential for further reduction in operating costs, whereas maintenance costs can be further reduced. Maintenance costs are especially of concern for companies with ageing aircraft fleets, as the inspection manpower requirement increases over the lifespan of the aircraft [2]. The adaptation and integration of current nondestructive testing (NDT) techniques for structural health monitoring (SHM) at damage critical locations offers the potential to reduce inspection time and cost. The detection of defects in the different layers of the multi-layered aircraft structure is one of the requirements for future SHM systems [3]. Only some of the NDT techniques used today, such as ultrasonic testing (UT) and eddy currents, are considered to be mature enough for use in SHM systems [4]. Eddy current technology has been proven for the detection of fatigue cracks in aircraft structures [5, 6], but for the use in future SHM systems has the disadvantage that only local damage monitoring, e.g., at a single fastener hole, can be achieved. UT is used for the detection of fatigue cracks at fastener holes in aircraft. Under laboratory conditions and with the presence of a sealant/adhesive layer, small defects (0.025 inch EDM notch) in the 2nd layer have been detected [7]. Recently a group at QinetiQ developed a similar UT technique for 2nd layer defect detection [8]. However, 2nd layer defect detection using conventional...
UT techniques can be problematic if the coupling medium (sealant) between the layers around the fastener hole is inadequate or missing [5, 8].

The possibility of fatigue crack detection at fastener holes in multi-layered structures using high frequency guided ultrasonic waves (5 MHz) has been investigated by Lindgren et al. [9]. Results from their work show that defect detection is possible, but that the detection sensitivity depends on the interface conditions between the layers. The authors also noted that high frequency guided ultrasonic waves are attenuated, if a material, such as an adhesive, is present between the metallic layers, making the monitoring of large areas difficult. According to Dalton et al. [10] potential guided wave modes used for large area inspection of double-layered metallic fuselage structures should have frequencies below 1 MHz to avoid attenuation over short distances. Therefore it is important to identify and study low frequency guided ultrasonic wave modes that are insensitive to interface conditions, but offer good sensitivity for defect detection. A flexural mode similar to the A0 mode has energy distributed through the thickness of the multi-layered structure [11], allowing in principle defect detection in all layers. In the frequency range of interest the phase and group velocity of this A0-like mode are insensitive to local thickness or material property variations of the sealant layer [12]. Most of the energy of the wave pulse can be propagated past areas with lack of sealant or adhesion with minimal time lag. Utilizing such a mode in the low frequency regime could overcome difficulties such as missing sealant and attenuation, offering potential benefits for the inspection and SHM of large parts consisting of multiple layers. However, low frequency guided ultrasonic waves have wavelengths significantly larger than commonly used in bulk wave UT, therefore the sensitivity for the detection of fatigue defects needs to be ascertained.

In this contribution the application of low frequency guided ultrasonic waves for the in-situ monitoring of fatigue crack growth in a multi-layered tensile specimen, consisting of two adhesively bonded aluminum alloy plate-strips, has been investigated. The guided waves in the tensile specimen were excited using piezoelectric discs and the resulting wave field was measured using a laser interferometer. Wave modes and dispersion relations for the multi-layered tensile specimen were calculated using a semi-analytical finite-element (SAFE) model. The wave propagation along the specimen was simulated from three-dimensional (3D) Finite Element (FE) calculations and compared to the experimental results. The influence of a fatigue defect in one of the metallic layers on the scattered field around the hole on the opposite layer was studied from FE simulations and experiments. Fatigue experiments were performed for 3 specimens and the amplitude of the guided ultrasonic wave field was monitored on-line at a single point using the laser interferometer.

2. Experiments
The multi-layered tensile specimens used for the fatigue testing (size: 600 mm x 40 mm x 6.2 mm) consist of two 3 mm thick aluminum alloy (2024-T6) plate-strips, adhesively bonded with a 0.2 mm thick adhesive layer (HYSOL-9394 EA) as shown in figure 1b. Three piezoelectric discs (Ferroperm Pz 27, diameter 5 mm, thickness 2 mm), permanently bonded using two-component epoxy glue 190 mm from the end of the specimen (figure 1a), were used for the excitation of the guided ultrasonic waves. Two of the discs were placed 4 mm from the respective side edges on the top layer (left in figure 1a) and one disc was placed in the centre of the opposite layer (right in figure 1a). This set up was chosen to excite a bending mode similar to the A0 mode in a single layer plate. The experimental setup shown in figure 1c was used. The excitation signal consisted of a 5 cycle, 115 kHz tone burst in a Hanning window and had narrow bandwidth. The signal was generated using an arbitrary function generator (Agilent 33220A), amplified (Krohn-Hite 7602M) and applied to the three piezoelectric discs. The excitation frequency was well below the thickness resonance of the PZT discs, which vibrate in a piston-like mode [13] and apply mostly an out-of-plane force to the specimen. For all of the experiments the velocity of the out-of-plane displacement was measured using a heterodyne laser interferometer (Polytec OFV 505/5000).
Figure 1. a) Schematic view (not to scale) of excitation setup and monitoring grid for wave propagation measurements; location of PZT discs (left: top layer; right: bottom layer); b) dimensions of multi-layered tensile specimen (600 mm x 40 mm x 6.2 mm); c) experimental setup.

The demodulated output signal obtained from the interferometer was band-pass filtered (Krohn-Hite 3988) around the centre frequency and averaged (20 times) in a digital storage oscilloscope (LeCroy 9304). Three different types of measurements were performed to study the wave propagation in the specimen, the influence of a crack on the scattered field around a fastener hole and to monitor fatigue crack growth. For the wave propagation in the multi-layered tensile specimen without a fastener hole, point wise measurements were taken on a Cartesian grid (figure 1a) every 2 mm in the z-direction and every 1 mm in the x-direction. The influence of a fatigue defect in the bottom layer on the scattered field around the fastener hole was studied. The through hole (diameter 6 mm) was drilled 300 mm from the end of the specimen (110 mm from PZT discs, figures 1b, 2a). Measurements were taken on the top, opposite layer on a radial grid around the fastener hole, every 5° in the angular direction and every 1 mm in the radial direction (red area in figure 2b, r = 4 mm to r = 12 mm). Measurements at one specimen were taken before the start of the fatigue experiments and repeated after a 4.8 mm long fatigue crack had been grown through the bottom layer. For the fatigue experiments three specimens were subjected to cyclic tensile loading in a servo-hydraulic testing machine (figure 2c). A maximum load of 30 kN was selected so that the maximum stress in the vicinity of the hole reached about 95% of the yield limit (stress concentration factor $K_t \approx 3.1$), in order to remain in the range of elastic deformation. The cyclic loading was performed with a stress ratio of $R = 0.1$ and cycling frequency of 10 Hz. An about 0.35 mm long starter notch was placed at the corner of the hole with the free surface of the bottom layer to control the crack location. After crack initiation the cyclic loading was stopped every 1000 cycles and the maximum tensile load was applied to avoid crack closure. The crack length on the bottom layer surface and depth in the fastener hole were measured optically using a microscope (specimen 1: only surface crack length). The amplitude of the guided ultrasonic wave amplitude was measured at a single point ($z = -3$ mm, $x = 3$ mm relative to the centre of the hole; shown as white dot in figure 2b).
3. Guided wave propagation in tensile specimen

A semi-analytical finite-element (SAFE) code developed at the University of Bordeaux [14] was used to obtain the dispersion diagram and mode shapes for the guided ultrasonic wave propagation in the multi-layered tensile specimen. Using SAFE the cross-section of the structure is discretized using 2D elements by assuming wave propagation along the length of the specimen, reducing the 3D problem to an equivalent 2D problem. The eigenvalue problem for each frequency is solved numerically and the corresponding mode shapes and wave numbers are calculated. Results obtained from the SAFE calculations show that in the frequency range of interest, which was well below the cut-off frequencies of higher order thickness modes for an equivalent infinite multi-layered plate, the tensile specimen shows multiple modes across the width (figure 3a). The four types of modes can be classified (similar to [15]) as flexural in the thickness direction (Fx), flexural in the width direction (Fy), torsional (T) and longitudinal (L).

Figure 3. a) Dispersion diagram for multi-layered tensile specimen: torsional modes (T), longitudinal modes (L), flexural modes in thickness direction (Fx), and flexural modes in width direction (Fy); b) dispersion diagram showing only flexural modes in thickness direction (Fx, blue, diamonds) and $A_0$-like flexural mode (red, solid) for an infinite multi-layered plate (same thickness).
The excitation setup described above will mainly excite flexural modes with the largest displacement in the thickness direction (figure 3b). Higher order modes are denoted with a number, e.g., Fx1 is the first higher order flexural mode in the thickness direction with a cut-off frequency of 20 kHz. At the chosen excitation frequency of 115 kHz there are three modes propagating, namely, Fx, Fx1, and Fx2. From figure 3b it can be seen that the dispersion curve of the lowest flexural mode Fx agrees very well with the $A_0$-like mode in an infinite multi-layered plate [15]. For the frequency range of interest the dominant out-of-plane displacement of these bending modes does not vary significantly through the thickness (figure 4d-f). Due to the lower stiffness of the adhesive layer, the in-plane displacement in each of the metallic layers is similar to the in-plane displacement of an $A_0$ mode in a single layered plate with the same thickness as one of the adherents [16]. In figure 4 the mode shapes through the thickness for the three flexural modes are compared to the $A_0$-like bending mode. The mode shapes for the Fx mode (figure 4d) and the Fx1 mode (figure 4e) agree well with the mode shape of the $A_0$-like bending mode in an infinite plate, while a slight difference, mostly for the in-plane displacements, can be seen between the Fx2 mode and the $A_0$-like mode (figure 4f). This suggests that the flexural modes have similar sensitivity for defect detection as the $A_0$-like mode, which could be employed for the inspection of large multi-layered structures. From the SAFE calculations it was found that the mode shape across the width of the lowest flexural mode (Fx) is almost constant (figure 4c), while the higher order modes, Fx1 (figure 4b) and Fx2 (figure 4a) have a standing wave amplitude pattern across the width. In order to try to excite the Fx1 mode above the cut-off frequency of the Fx2 mode (75 kHz), 3 PZT discs were placed at the nodes of the Fx2 mode ($x = -16$ mm and $x = 16$ mm, see figure 4a) and at the centre of the plate strip. FE simulations were carried out using a 3D model in ABAQUS/Explicit to investigate the wave propagation in the tensile specimen. The geometry was approximated with a Cartesian mesh (plates: 0.5 mm x 0.5 mm x 0.75 mm, sealant: 0.5 mm x 0.5 mm x 0.1 mm).

![Figure 4](image_url)

**Figure 4.** Mode shapes (out-of-plane amplitude) across the width: a) Fx2; b) Fx1, c) Fx; mode shapes through the thickness, out-of-plane displacement (red, solid) and in-plane displacement (blue, solid) for Fx, Fx1, and Fx2, out-of-plane displacement (green, dashed) and in-plane displacement (black, dashed) for the $A_0$-like bending mode: d) Fx; e) Fx1; f) Fx2; grey area: aluminum adherent; red area: adhesive layer.
The piezoelectric discs used in the experiments were modelled as out-of-plane point forces at the excitation locations and the wave field was monitored on a Cartesian grid. The excitation setup used for the experiments did not excite a single mode (Fx1) as intended, but excited multiple flexural modes. This lead to the amplitude variations seen along the width and length of the specimen in the FE simulations (figure 5a). These amplitude variations are caused by the interference between the flexural modes that can propagate at this frequency. The distance between two amplitude peaks at the centre of the specimen seen in figure 5a is about 60 mm. The measurement results in figure 5b show a similar amplitude variation to the FE simulations, but due to experimental variations the amplitude map is not symmetrical. For the study of the influence of a defect on the scattered field, the fastener hole was placed at a location of high amplitude 110 mm away from the excitation (z = 0 mm in figure 5b). The amplitude at this location is relatively constant, therefore locally around the fastener hole scattering similar to that of an A_{0r}-like bending mode in a large plate can be expected, as the mode shapes through the thickness are similar.

4. Influence of a fatigue crack on the scattered field

The influence of a fatigue crack in one of the layers on the scattered field around the fastener hole was investigated. The scattered field around the hole was measured before the start of the fatigue experiments and after a 4.8 mm long fatigue crack had been grown through the bottom layer at the right side of the hole. For the 3D FE simulations the defect was modeled as a zero width crack (5mm length) through the bottom layer. The fastener hole was approximated by removing elements from the Cartesian mesh. The measurement of the scattering around the hole without a defect (figure 6c) shows a similar amplitude pattern as the FE simulations (figure 6a), but is not perfectly symmetrical as the incident wave field is not symmetrical.
Figure 6. Amplitude of scattered field around hole ($r = 3$ mm) at centre frequency (115 kHz), incident wave propagating from bottom to top; a) FE simulation, no defect; b) FE simulation, 5 mm crack in bottom layer at right side of hole ($z = 0$ mm, $x = 3$ mm); c) experiment, no defect; d) experiment, 4.8 mm long fatigue crack in bottom layer at right side of hole ($z = 0$ mm, $x = 3$ mm).

Figure 7. Difference in amplitude at centre frequency (115 kHz) between the scattered field around fastener hole ($r = 3$ mm) with and without fatigue crack; incident wave propagating from bottom to top; a) FE simulation, 5 mm crack in bottom layer at right side of hole ($z = 0$ mm, $x = 3$ mm); b) experiment, 4.8 mm long fatigue crack in bottom layer at right side of hole ($z = 0$ mm, $x = 3$ mm).
From the FE simulations an additional reflection of the ultrasonic wave at the fatigue crack in the bottom layer is predicted, increasing the amplitude before the defect on the right side of the fastener hole and shifting the amplitude pattern (figure 6b). This change of the scattered field can be better observed from the difference of the amplitude patterns with and without a defect (subtraction of amplitudes shown in figures 6a and 6b), shown in figure 7a. An increase in amplitude of about 30% in front of the defect due to the interference with the additional scattered wave at the defect can be seen. In the area located behind the defect a decrease of about 15% is predicted. The experimental results (figure 6d) show a similar influence of the fatigue crack on the scattered field. The scattered field is shifted due to the presence of the defect. Behind the crack an amplitude decrease of about 30% was observed (figure 7b), while the amplitude increases by about 25% in front of the crack. The measurement point for the in-situ monitoring of the fatigue crack growth was chosen in the area in front of the crack location (figure 7b at z = -3 mm, x = 3 mm), where an amplitude increase is predicted for fatigue crack growth. Another possible location to monitor changes in the amplitude would be behind the crack, where an amplitude decrease was observed previously for a similar multi-layered specimen [17].

5. Fatigue crack growth monitoring

Cyclic loading of three tensile specimens was carried out as described in section 2. During the fatigue experiments, on-line monitoring of the guided ultrasonic wave amplitude at a single point on the top surface in front of the crack (see figure 2b) was performed using the laser interferometer. From the starter notch the crack grew with quarter elliptical shape in the bottom layer. Reaching the thickness of the bottom layer (3 mm), the crack continued to grow in length as a through crack in this layer. No cracking of the top layer was observed. Figure 8a shows the optically measured crack lengths (bottom surface length and depth) against the number of cycles for the three specimens (specimen 1 only surface length). For all three specimens crack initiation occurred between 20 000 and 30 000 cycles. After 45 000 cycles the fatigue crack had grown to a length of about 5 mm on the bottom surface. Figure 8b compares the amplitude of the guided ultrasonic wave at the single measurement point against FE simulations for the variation in crack length.

![Figure 8. a) Optically measured crack length on top surface (spec. 1: red, dashed; spec. 2: black, dashed; spec. 3: green, dashed) and crack depth inside hole (spec. 2: black, solid; spec. 3: green, solid) against number of cycles; b) measured ultrasonic amplitude at single monitoring point against optically measured surface crack length, normalized with initial amplitude (FE: blue; spec. 1: red; spec. 2: black; spec. 3: green),](image-url)
The monitored amplitude was normalized for each specimen with respect to the amplitude measured at the start of the fatigue experiment with no crack present. Good general agreement was found between the FE simulations and the experimental results for the 3 specimens (figure 8b). The amplitude of the guided wave at the monitoring location in front of the crack increases with increasing crack length. For a 5 mm long crack through the bottom layer the average measured amplitude increase for the three specimens is about 18% compared to a predicted 16% change for the FE simulations. This allows in principle for the detection of bottom layer fatigue cracks from guided ultrasonic wave measurements on the top layer. However, further investigations will be necessary to verify and improve the sensitivity for the detection of small cracks in real structures and to allow for remote detection without the necessity of local access to the fastener hole for the laser measurement.

6. Conclusions
The possibility of using low frequency guided ultrasonic waves for the monitoring of fatigue crack growth at fastener holes in multi-layered tensile specimens was investigated. The wave propagation in the multi-layered tensile specimen was predicted from SAFE and 3D FE calculations. Amplitude variations along and across the specimen were observed, indicating multiple flexural modes (across the width) propagating at the frequency of interest. The thickness mode shapes of the flexural modes show good agreement with an $A_0$-like bending mode in an infinite multi-layered plate, predicting similar sensitivity for defect detection. The amplitude of the scattered field around the hole with and without a defect was recorded on the top layer experimentally and from 3D FE simulations, showing a similar amplitude pattern for the undamaged case. The influence of a fatigue crack in the bottom layer on the scattered field was investigated. The scattered field obtained from the FE calculations for a defect showed good qualitative agreement with measurements, predicting a shift of the scattered field and an increase in amplitude in front of the defect. The amplitude at one point close to the defect was monitored during cyclic loading of three tensile specimens. Results from the on-line monitoring of fatigue crack growth and FE simulations showed a change in amplitude of the guided ultrasonic wave field with increasing crack length. The measured ultrasonic wave amplitude increase for the three specimens shows some variation but agrees well with the predicted increase from FE simulations. The measurement of the guided wave amplitude change allows in principle for the detection of fatigue cracks from the laser measurements close to the fastener hole. The sensitivity of the technique employing low frequency guided ultrasonic waves for the detection of fatigue cracks in tensile specimens has been investigated in this contribution. In order to employ this technique for future aircraft SHM applications, a number of steps would have to be implemented to ascertain the realistic application, reliability, and robustness of this technique for large multi-layered structures.

Acknowledgements
This work was supported by grant EP/D065011/1 from the UK Engineering and Physical Sciences Research Council (EPSRC).

References
[1] Speckmann H and Henrich R 2004 Structural health monitoring - overview on technologies under development Proceedings of the 16th World Conference on NDT, Montreal, Canada
[2] Sampath S G 1996 Aging combat aircraft fleets - long term applications NATO AGARD LS-206, Neuilly-sur-Seine, France
[3] Smith C D 1996 Federal Aviation Administration Aircraft Inspection Research and Development Programs Nondestructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware ed. by Rempt R D and Broz A L SPIE Conference Proceedings 2945 200-09
[4] Boller C 2000 Next generation structural health monitoring and its integration into aircraft design Int. J. Syst. Sci. 31 1333-49
[5] Lindgren E, Knopp J S, Aldrin J C, Steffes G J and Buynak C F 2007 Aging aircraft NDE: capabilities, challenges and opportunities in Review of Progress in Quantitative NDE 26 ed. by Thompson D O and Chimenti D E AIP Conference Proceedings 894 1731-38

[6] LaRiviere S G and Thompson J 1998 Development of reliable NDI procedures for airframe inspection NATO RT0 MP-10- Paper 7, Brussels, Belgium

[7] Lindgren E, Judd D, Concordia M, Mandeville J, Aldrin J C, Spencer F, Fritz D, Pratt E, Waldbusser R and Mullis R T 2004 Validation and deployment of automated ultrasonic inspections for the C-130 center wing ASIP Conference Savannah, Georgia

[8] Smith R A, Edgar D, Jones L D and Percivall D M 2005 An ultrasonic solution for second-layer crack detection Insight 47 81-84

[9] Lindgren E, Aldrin J C, Jata K, Scholes B and Knopp J 2007 Ultrasonic plate waves for fatigue crack detection in multi-layered metallic structures Health Monitoring of Structural and Biological Systems ed. by Kundu T SPIE Conference Proceedings 6532 53207

[10] Dalton R P, Cawley P and Lowe M J S 2001 The potential of guided waves for monitoring large areas of metallic aircraft fuselage structure J. Nondestr. Eval. 20 29-46

[11] Rokhlin S I 1991 Lamb wave interaction with lap-shear adhesive joints: theory and experiment J. Acoust. Soc. Am. 89 2758-65

[12] Lowe M J S and Cawley P 1994 The applicability of plate wave techniques for the inspection of adhesive and diffusion bonded joints J. Nondestr. Eval. 13 185-200

[13] Guo N and Cawley P 1991 Transient response of piezoelectric discs to applied voltage pulses Ultrasonics 29 208-17

[14] Predoi M V, Castaings M, Hosten B and Bacon C 2007 Wave propagation along transversely periodic structures J. Acoust. Soc. Am. 121 1935-44

[15] Mukdadi O M, Dessai Y M, Datta S K, Shah A H and Niklasson A J 2002 Elastic guided waves in a layered plate with rectangular cross section J. Acoust. Soc. Am. 112 1766-79

[16] Seifried R, Jacobs L J and Qu J M 2002 Propagation of guided waves in adhesive bonded components NDT & E Int. 35 317-28

[17] Kostson E and Fromme P 2009 Defect detection in multi-layered structures using guided ultrasonic waves in Review of Progress in Quantitative NDE 28 ed. by Thompson D O and Chimenti D E AIP Conference Proceedings 1096 209-16.