NDT&E International 71 (2015) 1–7

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

In-situ monitoring of fatigue crack growth using high frequency guided waves

B. Masserey [a], P. Fromme [b,*]

[a] Department of Mechanical Engineering, University of Applied Sciences, Fribourg, Switzerland
[b] Department of Mechanical Engineering, University College London, London WC1E 7JE, UK

ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form
13 December 2014
Accepted 19 December 2014
Available online 29 December 2014

Keywords:
Fatigue crack
Monitoring
High frequency guided ultrasonic waves
P/E measurement
Lamb wave modes

ABSTRACT

The development of fatigue cracks at fastener holes represents a common maintenance problem for aircraft. High frequency guided ultrasonic waves allow for the monitoring of critical areas without direct access to the defect location. During cyclic loading of tensile, aluminum specimens fatigue crack growth at the side of a fastener hole was monitored. The changes in the energy ratio of the baseline subtracted reflected guided wave signal due to the fatigue damage were monitored from a stand-off distance using standard ultrasonic pulse–echo measurement equipment. Good sensitivity for the detection and monitoring of fatigue crack growth was found.

1. Introduction

The development of fatigue cracks at fastener holes in aluminum components is a common maintenance problem for the aircraft industry [1]. Especially the development of widespread fatigue damage due to stress concentration and cyclic loading conditions constitutes a safety-critical problem for ageing aircraft [2]. Different nondestructive testing (NDT) methods have been developed for the early detection of fatigue cracks [3]. Some of them require direct access to the inside of the fastener hole [3], complicating the possible integration into a structural health monitoring (SHM) system. Ultrasonic bulk wave measurements have a proven track record and sensitivity for the detection and sizing of cracks [4]. The real time, in-situ monitoring of fatigue cracks at fastener holes using an angle beam through transmission technique has been demonstrated [5]. However, bulk wave ultrasonic testing necessitates local access to the damaged area of the inspected structure.

Guided ultrasonic waves have been proposed for the integration into SHM systems, as with appropriate mode selection they offer the required area coverage [6]. Most work has focused on the selective excitation of one of the fundamental modes (A_0 and S_0 Lamb wave modes) below the cut-off frequencies of the higher wave modes [7], as this allows simpler signal interpretation and typically lower attenuation for realistic aircraft structures [8]. The scattering of guided waves at a hole with and without a fatigue crack has been investigated [9]. Guided waves have been successfully employed to detect and monitor fatigue crack growth in metallic structures [10], and this has been extended for the monitoring of a series of through holes with multiple crack initiation sites [1]. However, low frequency guided waves have a wavelength significantly larger than in bulk wave ultrasonic testing, ultimately limiting the sensitivity for the detection of small defects [11]. The shorter wavelengths of surface acoustic waves propagating along a structure have been employed for enhanced fatigue crack monitoring sensitivity [12].

High frequency guided ultrasonic waves offer an interesting compromise between the proven defect detection sensitivity of bulk ultrasonic waves and achievable propagation range. Different modes and frequency-thickness operating ranges have been investigated for defect detection over medium long distances, e.g., for corrosion detection in aircraft panels [13] and defects in plate structures [14]. With the appropriate choice of wave mode excitation good detection sensitivity for small surface defects and the potential to differentiate the damaged plate side have been demonstrated [15]. Previous work has found good sensitivity for the early detection and monitoring of fatigue crack growth during cyclic loading using noncontact laser measurements close to the damage location [16]. The two fundamental Lamb wave modes were excited selectively at a frequency-thickness product of 6.75 MHz mm, significantly above the cut-off frequencies of the higher Lamb wave modes [17]. The scattering of this type of high frequency guided waves from fatigue cracks at a

* Corresponding author. Tel.: +44 207 679 3944.
E-mail address: p.fromme@ucl.ac.uk (P. Fromme).

http://dx.doi.org/10.1016/j.ndteint.2014.12.007
0963-8695/

fastener hole had been previously measured and compared to numerical predictions in order to understand and quantify the potential detection sensitivity [18].

This contribution extends this work to the experimental in-situ monitoring of fatigue crack growth in tensile, aluminum specimens from a stand-off distance from the fastener hole without direct, local access to the damage. The high frequency guided waves were excited using a standard angle beam transducer and monitored using standard ultrasonic pulse–echo equipment. The fatigue crack growth was measured optically during cyclic loading and the changes in the reflected high frequency guided ultrasonic wave pulse were quantified. Calculating the energy ratio of the time-gated and baseline subtracted guided wave reflected pulse–echo (P/E) signal, good sensitivity of the measured changes with crack size were confirmed.

2. High frequency guided ultrasonic wave propagation

High frequency guided waves represent a compromise between achievable propagation distance along plate structures and sensitivity for the detection of small defects due to their relative short wavelength [14]. For this investigation the fundamental anti-symmetric (A_0) and symmetric (S_0) Lamb modes at a frequency-thickness region of about 6.75 MHz mm were excited in a plate (center frequency of 2.25 MHz for a 3 mm thick structure). These modes are easily generated and received with sufficient selectivity above the cut-off frequencies of the higher Lamb wave modes using standard angle beam transducers [17]. In this frequency region the wavelength equals approximately half of the plate thickness and the A_0 and S_0 modes have modeshapes with stress and displacement fields similar to a Rayleigh wave on each plate surface. However, for excitation on the upper surface there is small residual amplitude at the lower boundary, causing a coupling between the two surfaces. This gives rise to an energy transfer from one side of the plate to the other and then back over a distance called the beatlength [19]. The beatlength L can be calculated as

$$L = \frac{2\pi}{k_{A_0} - k_{S_0}}, \tag{1}$$

where k_{A_0} and k_{S_0} are the wave numbers of the fundamental anti-symmetric and symmetric Lamb modes. The beatlength depends on the difference between the wave numbers k_{A_0} and k_{S_0} in the denominator term. With increasing frequency the difference between wave numbers decreases and thus the beatlength increases. For a frequency of 2.25 MHz mm the difference in wave number (and thus phase velocity) between the fundamental anti-symmetric and symmetric Lamb modes is about 0.5%, resulting in a beatlength L=250 mm for a 3 mm thick aluminum plate. The associated beating phenomenon can be used for the detection of small cracks on both plate sides with single-sided access or, selecting appropriate excitation frequency and position, for the inspection of structures where access is restricted by regularly spaced features such as stiffeners or stringers [17].

Fig. 1 shows the group velocity dispersion diagram for the used 3 mm thick aluminum plate specimens. The group velocities of the fundamental Lamb wave modes (A_0 and S_0) are shown as solid lines. These have been widely employed for SHM applications in large structures at low frequencies [6]. In the frequency range of interest around 2.25 MHz the fundamental modes are rather non-dispersive and the velocities start to converge towards the Rayleigh wave velocity (2918 m/s). The group velocity of the A_0 mode for 2.25 MHz at 2948 m/s is slightly higher than the group velocity of the S_0 mode at 2879 m/s, resulting in a relative difference of the expected arrival times of about 2.5%.

3. Experiments

Five tensile specimens with length 600 mm, width 70 mm, and thickness 3 mm (Fig. 2), made of aluminum alloy 2014 T6, were used for the fatigue testing. A 1/4 in. diameter hole (r=3.17 mm) was drilled on the center line at 200 mm from the specimen end (Fig. 2). The specimens were subjected to cyclic tensile loading in a servo-hydraulic testing machine (Fig. 3(a)) with the axis of loading along the specimen length. A maximum load of 26 kN with stress ratio R=0.1 and a cycling frequency of 10 Hz were selected. The maximum stress in the vicinity of the hole (stress concentration factor K_t=2.75) was significantly above the fatigue strength of the aluminum alloy, but just below the yield limit in order to avoid plastic deformation. A small triangular starter notch, approximately 0.2 mm long, was made on one side of the specimen at the hole boundary (perpendicular to the loading axis) in order to prescribe the crack initiation location. During fatigue testing the crack grew quarter-elliptically from the starter notch position to a length and depth of about 3 mm. At that depth, corresponding to the specimen thickness, the crack quickly developed into a through-thickness crack.

The cyclic loading was paused every 1000 cycles and the specimen held under the maximum tensile load to avoid crack closure. The crack size was measured optically on the front surface (crack

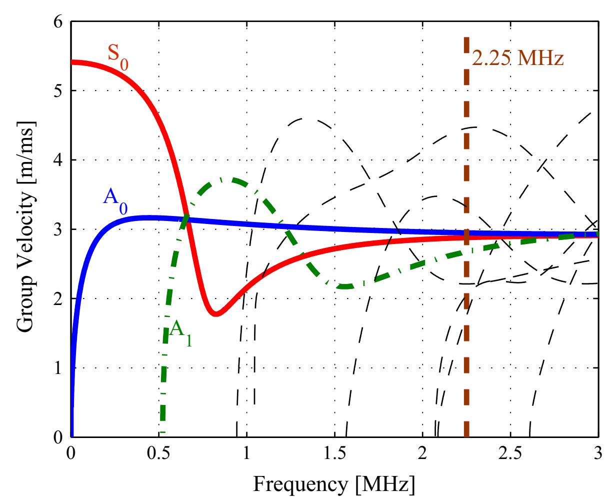

Fig. 1. Group velocity dispersion diagram for 3 mm thick aluminum plate (Al 2014 T6); fundamental modes (A_0 and S_0): solid lines; A_1 mode: dash-dotted line; higher order modes: dashed lines; center frequency 2.25 MHz marked.

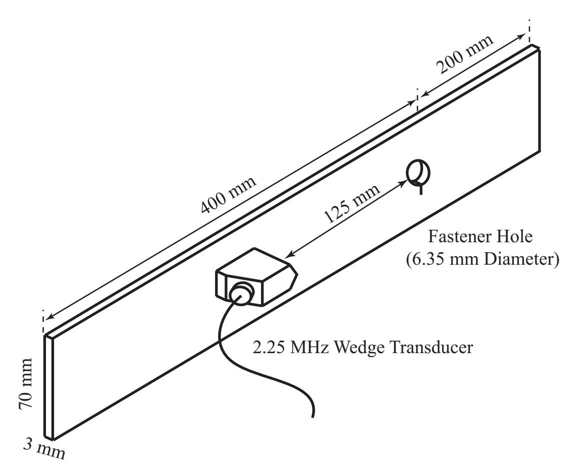

Fig. 2. Schematic of tensile specimen (Al 2014 T6, 600 mm × 70 mm × 3 mm) with fastener hole (1/4 in./6.35 mm diameter) and location of 2.25 MHz wedge transducer.