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High-frequency guided ultrasonic waves for hidden defect detection in multi-layered aircraft structures

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ABSTRACT

Aerospace structures often contain multi-layered metallic components where hidden defects such as fatigue cracks and localized disbonds can develop, necessitating non-destructive testing. Employing standard wedge transducers, high frequency guided ultrasonic waves that penetrate through the complete thickness were generated in a model structure consisting of two adhesively bonded aluminium plates. Interference occurs between the wave modes during propagation along the structure, resulting in a frequency dependent variation of the energy through the thickness with distance. The wave propagation along the specimen was measured experimentally using a laser interferometer. Good agreement with theoretical predictions and two-dimensional finite element simulations was found. Significant propagation distance with a strong, non-dispersive main wave pulse was achieved. The interaction of the high frequency guided ultrasonic waves with small notches in the aluminium layer facing the sealant and on the bottom surface of the multilayer structure was investigated. Standard pulse-echo measurements were conducted to verify the detection sensitivity and the influence of the stand-off distance predicted from the finite element simulations. The results demonstrated the potential of high frequency guided waves for hidden defect detection at critical and difficult to access locations in aerospace structures from a stand-off distance.

1. Introduction

During the service life of aerospace structures damage can occur due to cyclic loading conditions [1]. Common maintenance problems include disbonds of the sealant layers connecting multiple metallic sheets and the development of fatigue cracks. Such structures must therefore be regularly inspected non-destructively to detect hidden damage such as fatigue cracks before they have reached a critical length. Recently an ultrasonic-based structural health monitoring method has been developed for real time, in situ monitoring of cracks at fastener holes using an angle beam through transmission technique [2]. Standard bulk wave Ultrasonic Testing (UT) has a proven sensitivity for the detection of small defects, e.g., shear wave angle beam measurements [3]. However, it often necessitates local access and time-consuming scanning of the inspected part [4]. Rayleigh waves have been used for the detection of surface fatigue cracks in metallic plates [5]. Analytical models have been developed to describe the interaction of Rayleigh waves with surface cracks [6], as well as numerical simulations complemented by experimental results [7]. Typically damage detection using Rayleigh waves requires access to the side of the structure containing the defect.

Large areas of plate structures can be inspected and monitored from a single, remote access point using guided ultrasonic waves [8]. These are often used in a low frequency-thickness range below the cut-off frequency of the higher wave modes to simplify data interpretation [4]. However, the resulting wavelengths are typically significantly larger than in bulk wave UT, thus limiting the sensitivity for the detection of small defects [9]. The interaction of low frequency guided waves with small surface defects in plates has been studied using Finite Element (FE) simulations and experiments [10]. The propagation of guided ultrasonic waves in bonded components [11] and the interaction with holes in metallic plates has been investigated [12]. Low-frequency guided ultrasonic waves were used for the detection of fatigue cracks at fastener holes [13].

The application of guided ultrasonic wave modes in the higher frequency-thickness range has more recently been investigated

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for non-destructive testing purposes. The S_0 mode (around 5 MHz mm) was used for corrosion detection in aircraft structures [14], and longitudinal modes (above 15 MHz mm) were employed for plate inspection [15]. This type of waves allows for the inspection of structures over reasonably long distances, and can be used even if local access to the inspected part is not possible [4]. The employed wavelengths are comparable to those commonly used in bulk wave UT, possibly allowing good sensitivity for the detection of small defects [15]. High frequency guided waves excited using standard 90° angle beam transducers at around 6.75 MHz mm can be interpreted as the superposition of the first anti-symmetric A_0 and symmetric S_0 Lamb wave modes [16]. These waves can propagate along the structure and allow for the inspection of both plate surfaces due to an energy transfer between the surfaces. A hybrid analytical/numerical model was developed to describe the wave propagation and the reflection at small surface defects in single layer metallic plates [17]. From standard pulse-echo measurements the location and damaged plate side of small surface defects in aluminium plates could be determined using a combination of time-of-flight and frequency evaluation of the reflected pulse, [18]. Fatigue crack growth at a fastener hole in tensile, aluminium specimens was detected and monitored in situ using non-contact measurement of high frequency guided ultrasonic waves [19]. The detection of defects in the different layers of multi-layered aircraft structures is one of the requirements for future Structural Health Monitoring (SHM) systems [20]. A UT technique for 2nd layer defect detection has been developed using an angled phase-array probe and automated analysis of the acquired ultrasonic signals [21]. 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 [21]. Guided ultrasonic waves have energy distributed through the thickness of the multi-layered structure, making it in principle possible to inspect the different layers. Low frequency guided ultrasonic waves were employed to monitor fatigue crack growth at a fastener hole in a multi-layered structure [22]. The potential for the detection of real defects in an inaccessible layer was demonstrated, but a limited sensitivity for the detection of fatigue crack growth initiation was noted. The possibility of fatigue crack detection at fastener holes in multi-layered structures using high frequency guided ultrasonic waves (5 MHz) has been investigated [23]. It was shown that defect detection is possible, but that detection sensitivity depends on the interface conditions between the layers. It was 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 more difficult.

In this contribution the potential of high frequency guided ultrasonic waves for the detection of hidden defects in multi-layered aerospace structures has been investigated. These waves can propagate over medium distances and are in principle sensitive for defect detection through the complete specimen thickness. The wave propagation characteristics of high frequency guided wave modes excited using a standard 90° angle beam wedge in a multi-layered model structure have been studied. The structure consists of two adhesively bonded aluminium plates with an epoxy based sealant layer [24]. Interference occurs between the wave modes during propagation along the structure, resulting in a frequency dependent variation of the energy through the thickness with distance. Finite Element (FE) simulations have been carried out and compared to laboratory measurements using a laser interferometer. The sensitivity for the detection of an internal notch at the sealant layer and on the bottom surface of the multilayer structure from a stand-off distance using pulse-echo (P/E) measurements has been demonstrated.

2. Experimental details

2.1. Specimen preparation

The multilayer structure model investigated in this contribution was made of two 3 mm thick aluminium plates with a width of 70 mm and a length of 600 mm connected with an approximately 0.25 mm thick epoxy based sealant layer, see Fig. 1. The plate material is an aluminium alloy 2014 T6 widely used for aerospace applications, having a Young's modulus of 73.1 GPa, Poisson's ratio of 0.33, and density of 2800 kg/m^3. The sealant is a two-part structural paste adhesive Hysol EA 9394 with a Young's modulus of 4.237 GPa (data from supplier), density of 1360 kg/m^3, and Poisson's ratio of 0.45. Measurements of the Young's modulus have been performed on a moulded 120 mm × 15 mm × 3 mm epoxy specimen in a standard tensile machine to confirm the material properties specified by the supplier. The relative error between the measured and the supplier value was below 1%. The thickness of the sealant layer was controlled by mixing approximately 4% volume fraction of spacer beads with a maximum diameter of 0.249 mm into the epoxy paste and clamping the specimen during curing at room temperature. To control the accuracy and the reproducibility of the sealant layer, the thicknesses of the different layers were measured along the centreline of the specimens in 1 mm step size using a coordinate measuring machine. The sealant thickness was obtained by subtraction of the aluminium thicknesses (measured before application of the epoxy paste) from the total multilayer thickness (measured after curing). The resultant thickness on the centreline was measured as varying between 0.22 mm and 0.28 mm, with an average sealant thickness of approximately 0.25 mm. Multiple specimens without defects were manufactured in order to investigate the high frequency guided ultrasonic wave generation and propagation in multilayer structures. More specimens were manufactured with an artificial defect. The notch was placed either in one of the aluminium plates at the interface between aluminium and sealant, as illustrated schematically in Fig. 1(b), or on the bottom surface of the multilayer structure. The notch was cut across the width of the specimen to a depth of 0.3 mm using an Electro-Discharge Machining (EDM) device. Restrictions of the EDM device imposed a notch width of approximately 0.4 mm and a maximum specimen length of 550 mm. The notch was placed at 150 mm from one end of the specimen. A wire covered with Teflon tape was placed into the notch to avoid sealant ingress during sealant application. The tape was removed after curing of the epoxy paste.

2.2. Measurement setup

The high frequency ultrasonic guided wave was generated on the surface of the multilayer specimen using a standard 1 MHz half inch transducer mounted on a 90° angle beam wedge for steel. The spatial period of the generated ultrasonic field at the interface wedge-aluminium can be evaluated on the basis of the Rayleigh wavelength: performing the calculation for the transducer centre frequency leads to a wavelength λ_R of 3.0 mm, about half the thickness of the multilayer specimen. The wedge was clamped on the specimen so that the main propagation axis is the centre line of the multilayer specimen, as displayed in Fig. 1(a).

For the investigation of the wave propagation characteristics a five cycle tone burst at 1 MHz centre frequency (sinusoid in a Hanning window) was generated in an arbitrary waveform generator and amplified using a broadband power amplifier. The out-of-plane component of the surface velocity was measured along the centre line of the specimen (step size: 1 mm) using a heterodyne laser interferometer mounted on a scanning rig. The origin ($x = 0$)

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