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Highly accurate online characterisation of cracks in plate-like structures

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ABSTRACT

In this paper, an *in situ* technique for the localisation and the sizing of cracks in plate-like structures is presented. The excitation and the reception of the ultrasonic diagnostic signal – Lamb waves – are achieved by permanently installed piezoelectric ceramic disks. The technique simplifies the underdetermined problem of the full characterisation of cracks to an over-determined problem of the localisation of crack tips. Also, it overcomes the difficulties associated with using the pitch-catch excitation scheme for crack characterisation. The development of the technique was done systematically using analytic models and the finite element method. The technique has been validated by an experiment and assessed by extensive parametric studies. While it was designed to be a convenient approach, highly accurate crack characterisation has been attained as evident through the results of both numerical studies and physical experiments.

1. Introduction

The importance of structural integrity to critical engineering structures such as aircrafts and pressure vessels cannot be exaggerated. The condition inspection of these structures still very much depends on conventional non-destructive evaluation (NDE) techniques such as ultrasonic C-scanning and X-ray scanning. The execution of these techniques requires structures to be pulled out of service and hence incurs significant costs. More importantly, due to the extreme loading conditions that it is subjected to, a critical engineering structure may encounter failure before it is due for a scheduled inspection.

In recent years, the concept of online structural health monitoring (SHM) has attracted much attention and research effort. In particular, it has been shown that Lamb waves can be used effectively for the detection of defects in plate-like structures. The excitation and the reception of Lamb waves can be achieved efficiently by compact piezoelectric patches. To date, the types of defects, which Lamb waves have been able to detect, include, but are not limited to cracks [1–3], holes [4,5] and delaminations [6,7]. However, due to the underdetermined nature of the inverse problem, techniques for the sizing of cracks without *a priori* knowledge of locations have rarely been reported. Although phased array scanning has demonstrated such potential [8], it requires significantly large numbers of transducers and, yet, still struggles to characterise cracks that are not perpendicular to the purposely formed wave beams.

The technique presented in this paper fills in the abovementioned knowledge gap in the development of SHM. It utilises piezoelectric disks that are excited sequentially in the pulse-echo scheme. The pulse-echo excitation scheme, which processes back-scattered signals that are reflected off the features of interest, has been well studied and exploited for NDE [9]. For the detection of cracks on plate-like structures, it will not lead to situations in which an actuator-sensor path intersects with (passes through) a crack and hence outputs signals that give ambiguous information about the crack, as the pitch-catch excitation scheme will do. The detection and the sizing of cracks can be represented by the localisation of crack tips which are omni-directional scattering sources. If carefully executed, this can become a determined or even an over-determined problem. The signal features of interest are the time-of-flight's (ToFs) of the echoes from crack tips. The localisation of the tips of a crack is made possible by a two-stage approach. At first, the method of triangulation is used to provide the initial estimates of locations. Then, these estimates are further enhanced by a multilateration (MLAT) algorithm [10] and the removal of the sensor signals that involve interactions with the crack line.

The development of the technique made use of both analytic models and the finite element method (FEM). The analytic models were used for the tuning of diagnostic signal, and the FEM was employed to simulate the propagation of Lamb waves. The high accuracy of the technique in crack characterisation has been validated by an experiment. A series of parametric studies that were based on numerical simulations have also been carried out in order to obtain a comprehensive understanding of the performance of the technique.

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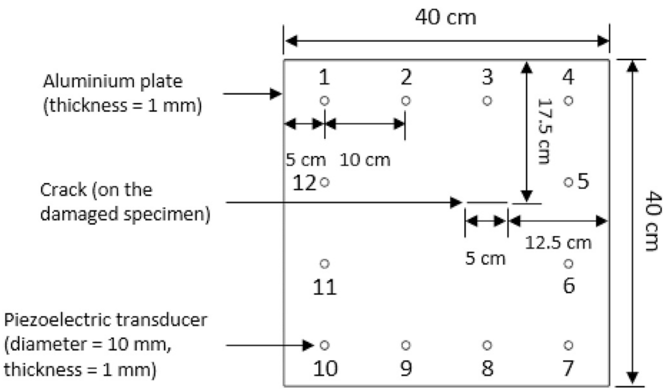

Fig. 1. Schematic diagram of the specimens used for the development of the technique (the transducers are numbered from 1 to 12 clockwise starting from the top left corner).

Table 1
Properties of the materials used for the specimens.

	Aluminium	Piezoelectric Ceramic
Density (kg/m^3)	2700	7800
Young's modulus (GPa)	70	100
Poisson's ratio	0.33	0.33

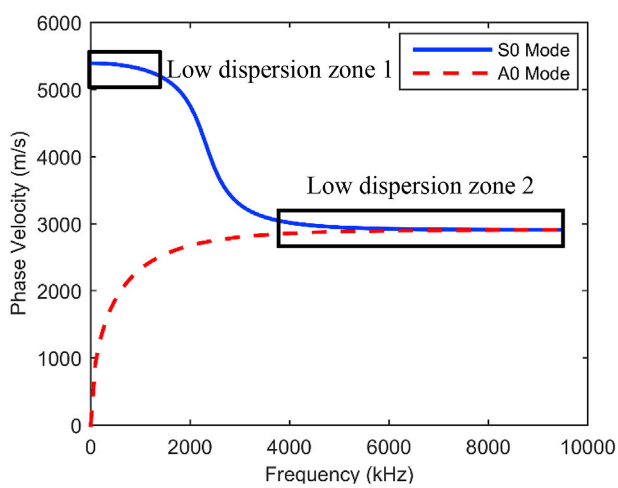

Fig. 2. Dispersion curves of the S0 and the A0 Lamb wave mode in a 1 mm thick aluminium plate.

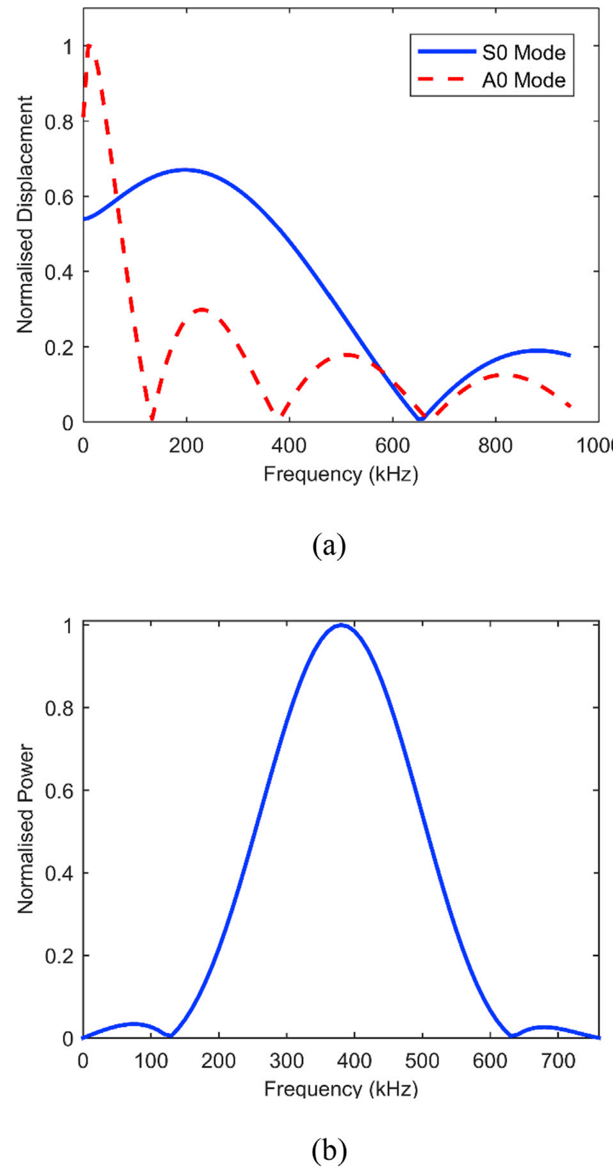

Fig. 3. (a) Displacements of the S0 and the A0 Lamb wave mode that are excitable at different frequencies by a piezoelectric disk with a diameter of 10 mm in a 1 mm thick aluminium plate. (b) Frequency spectrum of a three-cycle Hanning-windowed sinusoidal toneburst with a central frequency of 380 kHz.

2. Development of detection strategy

2.1. Specimens

The development of the technique is demonstrated using the pristine and the damaged specimen illustrated in Fig. 1. On each of the specimens, a network of 12 piezoelectric disks are permanently adhered. The area bounded by the piezoelectric disks is referred to as the *effective detection area*. It is expected that any crack within this area will be detectable.

The material properties of the aluminium plate and the piezoelectric disks are given in Table 1. Since the current technique does not take into account signal amplitudes, the electric and the piezoelectric properties of the transducers do not need to be considered.

2.2. Tuning of diagnostic signal

The dispersion curves of the two types of Lamb wave modes – the symmetric (S) and the anti-symmetric (A) mode – can be found by solving the Rayleigh-Lamb equations [11]. In Fig. 2, the dispersion curves of the two fundamental Lamb wave modes – the S0 and the A0 mode – in the aluminium plate shown in Fig. 1 are displayed.

The responses of a plate that is excited by a piezoelectric actuator have been studied by many [12–15]. At a certain frequency, the response of a certain Lamb wave mode (S0, A0, S1, A1, S2, A2, etc.) to the excitation induced by a piezoelectric disk is given by Ref. [15].

$$u(r) = iCaJ_1(ka)\frac{N(k)}{D'(k)}H_1^{(2)}(kr) \tag{1}$$

where for S modes,

$$N(k) = kq\left(k^2+q^2\right)\cos(pd)\cos(qd)$$

$$D(k) = \left(k^2-q^2\right)^2\cos(pd)\sin(qd) + 4k^2pq\,\sin(pd)\cos(qd)$$

and for A modes,