NDT and E International 98 (2018) 130–133

Contents lists available at ScienceDirect

NDT and E International

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

Towards in-plane local defect resonance for non-destructive testing of polymers and composites

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ARTICLE INFO

Keywords:
Local defect resonance (LDR)
In-plane resonance
Non-destructive testing (NDT)
Composite materials

ABSTRACT

Local defect resonance (LDR) makes use of high frequency vibrations to get a localized resonant activation of the defect. In this study, it is shown for various samples and damage features that the classical out-of-plane local defect resonance can be equally extended towards in-plane local defect resonance. It is found that the in-plane LDR typically occurs at higher frequencies, which is linked to the specific geometry of common defects. This increased frequency allows for a reduction in measurement time. More importantly, the results indicate that the in-plane LDR has an increased sensitivity for defects with dominant out-of-plane defect interfaces (e.g. surface breaking crack). Knowledge of both the out-of-plane and in-plane LDR provides further insight on the internal structure of a defective area. This is explicitly demonstrated on a carbon composite which was subjected to low velocity impact, inducing barely visible impact damage.

1. Introduction

Composite materials (e.g. carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP)) are widely used in many advanced engineering structures. Their high specific strength and resistance to fatigue and corrosion makes them especially attractive for transportation applications. A concern in the use of composite materials is related to the occurrence of and sensitivity to internal damage features. The damages are often invisible to the naked eye e.g. barely visible impact damage (BVID). Of utmost importance is a non-destructive testing (NDT) technique that can be used to detect and evaluate small damages.

In the past decade, NDT by high frequency modal testing (1–200 kHz) was proposed by Solodov et al. [1,2]. These high frequencies are used to get a localized resonant activation of the defected zones and is therefore named: Local Defect Resonance (LDR). The LDR concept is used successfully to detect flat bottom holes (FBH) [3–6], inserts [7–9], debonding [2,5] and BVID [3,4,7,10–12]. In general, the defect's location is revealed by measuring the out-of-plane surface response of a defected sample using a scanning laser Doppler vibrometer (SLDV).

In the present study, it is shown that the concept of LDR does not limit itself to out-of-plane characteristics, but can be extended towards in-plane characteristics. Indeed, the physical mechanism behind local resonation suggests that defects should also show a distinct in-plane resonation (often at elevated frequency compared to the classical out-of-plane LDR). This is experimentally demonstrated for three different types of damages (i) circular FBH in polymethyl methacrylate (PMMA), (ii) surface breaking crack in a laminated glass panel and (iii) BVID in CFRP.

2. Material and methods

The in-plane and out-of-plane vibrational response is obtained by using a 3D infrared scanning laser Doppler vibrometer (Polytec PSV-500-3D XTRA). The infrared wavelength shows optimal reflectivity for most surfaces. Orthogonal projection is used to calculate the velocity of vibration in the X, Y and Z direction where Z is defined as the out-of-plane component and X and Y are the two in-plane components in the left-to-right and bottom-to-top direction, respectively. This coordinate system is indicated on each figure. For all measurements, a scanning grid size between 1 and 2 mm is used. The extensions of the classical out-of-plane LDR towards in-plane LDR requires the measurements to be obtained using a 3D SLDV. A 3D SLDV is relatively expensive compared to a standard 1D SLDV. Though, recent research has resulted in a silicon-on-insulator multi-point homodyne vibrometer, which has been successfully

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https://doi.org/10.1016/j.ndteint.2018.05.007
Received 9 January 2018; Received in revised form 12 April 2018; Accepted 14 May 2018

used for the assessment of elastic waves propagating in an Aluminum plate [13]. This on-chip LDV comes with a significant reduction in production cost.

Three different samples are investigated, each containing a specific type of damage. The first sample contains square and round FBHs. It is manufactured by bonding a $300 \times 210 \times 0.5\,\text{mm}^3$ polystyrene sheet onto a 5 mm thick PMMA plate containing round and square holes of different sizes (see Fig. 1 (a)). Epoxy resin was used as adhesive. The second sample is a $400 \times 400 \times 5\,\text{mm}^3$ cracked laminated glass panel where the crack of interest starts at the vertical edge and ends at the closest horizontal edge (see Fig. 1 (b)). The crack runs only in the top glass panel (see inset on the figure), and thus is representative for a surface breaking crack. For the transparent glass panel, reflective tape was used on the cracked top plate for the SLDV measurements. The third sample is a $100 \times 200 \times 5.5\,\text{mm}^3$ CFRP plate manufactured from unidirectional carbon fiber layers with layup $[(0/90)]_{6s}$ (see Fig. 1 (c)). A 7.1 kg weight is dropped on the CFRP plate from a height of 0.1 m according to the ASTM D7136. This results in an impact energy of 7 J, which introduces BVID. The inset on the figure shows the hair-like surface breaking crack in the middle of the damaged area orientated along the X direction.

All three samples are excited using a low power piezoelectric (PZT) patch (type EPZ-20MS64W from Ekulit, with a diameter of 15mm). A burst chirp (i.e. fast swept sine signal followed by a zero signal) is used as excitation signal. The bandwidth of this signal is 60 kHz, 80 kHz and 180 kHz for the PMMA/polystyrene plate, glass panel and CFRP plate respectively. Out of the broadband signals, the LDR frequencies are selected by manual peak picking. A Falco System WMA-300 amplifier is employed to increase the energy input, resulting into a peak-to-peak voltage between 50 and 100 V_{pp}.

Typically, piezoelectric actuators have dominated out-of-plane actuation at lower frequencies. However, for the high frequencies involved in in-plane LDR, PZT patches show a substantial increase in in-plane actuation [14]. In order to further increase the excitation of in-plane vibration modes, the piezoelectric patches have been attached on the side of the sample in cases S1E2 and S3E2 (see Fig. 1). Alternative to this impractical side-excitation, one could also opt to use two identical piezoelectric discs attached on both top and bottom surface of the plate, and to drive them in phase in order to promote in-plane stimulation [15].

3. Results and discussion

3.1. PMMA/polystyrene plate with FBHs

Broadband excitation of the PMMA/polystyrene plate with square and round FBHs through the PZT glued to the surface (actuator S1E1) unveiled the presence of out-of-plane LDR (referred to as LDR_Z). The velocity magnitude map at the circular 21 mm FBH is shown in Fig. 2. The coordinate system in the lower left corner of each figure indicates which velocity component is plotted. Next to the fundamental LDR_Z, multiple higher order LDR_Z modes were found which clearly relate to the defect's shape (see Fig. 2(a–c)). These results are consistent with LDR_Z measurements reported in literature [4].

Next to the classical out-of-plane LDR, also distinct in-plane LDR modes (referred to as LDR_{XY}) were found at elevated frequencies. In order to increase the in-plane response in the Y direction, the results are shown for excitation through the PZT attached to the side (actuator S1E2). Fig. 2 (d) shows the Y-velocity component for the first order in-plane resonance for the circular FBH.

The shape of the FBH affects the LDR response. Especially for the in-plane components this is clear: one of the main factors in in-plane LDR concerns the length of the defect. Hence, a rectangular FBH will have different frequencies for the LDR_{XY} along its length direction compared to the LDR_{XY} along its width direction. The ratio of these two frequencies is related to the ratio of the length and width.

The in-plane LDR is typically triggered at higher frequencies due to the relatively high in-plane bending stiffness (or flexural rigidity) of the defected zone. A profound exploration of the possible advantages and disadvantages of this characteristic of LDR_{XY} with respect to possible automated defect identification procedures [5] is required. The elevated

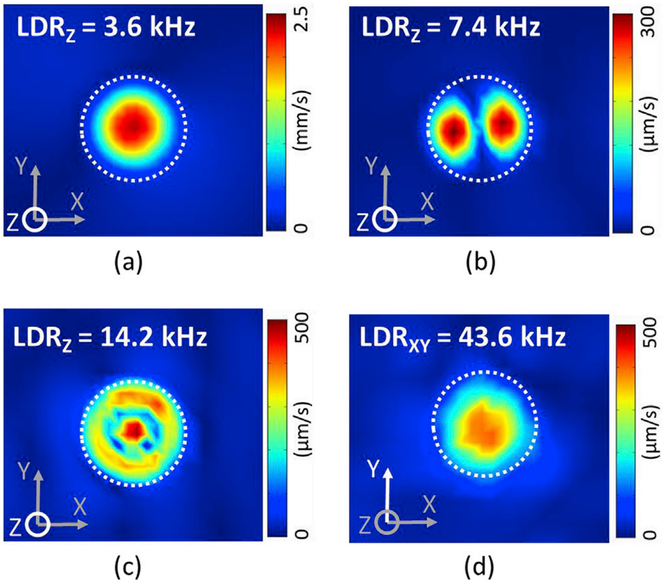

Fig. 2. Velocity magnitude map at LDR for a circular 21 mm FBH. (a–c) LDR_Z Z-velocity data (actuator S1E1). (d) LDR_{XY} Y-velocity data (actuator S1E2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

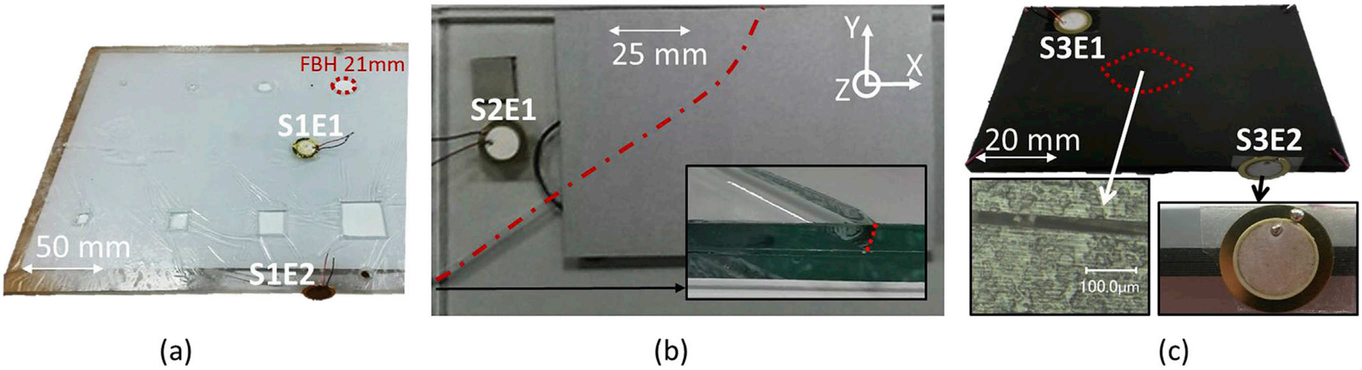

Fig. 1. Defected test samples. (a) PMMA/polystyrene plate with FBHs. (b) Laminated glass panel with surface breaking crack. (c) CFRP with low velocity impact damage. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)