

Listening for airborne sound of damage: a new mode of diagnostic Imaging



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Abstract

Resonant air-coupled emission (RACE) is a new method of detecting damage based on local damage resonance (LDR). Resonant vibrations in defect excite airborne acoustic wave, which emanates from the damaged area, and therefore could be used for diagnostic imaging. A conventional approach to RACE imaging uses C-scanning of flat surfaces with a microphone and provides high resolution imaging in the near field zone. In this paper, some features of RACE field are studied experimentally to recognize the possibility of imaging in transition zone between the near- and far-fields. A modification of the RACE scanning mode by using a robot is investigated to be applied to complex shape components. An alternative imaging technique proposed uses a microphone array and provides full-field visualization of RACE field. The 64 microphone acoustic camera array is applied for express testing and imaging. Multiple case studies are given to demonstrate the potential of the both modes for diagnostic imaging of simulated and realistic defects in polymers and composite materials.

Introduction

Lightweight fiber-reinforced composite materials are a continually growing sector of industry in recent years. Due to increasing demand of light parts in automotive and aviation, it is expected that production of composite materials will rise even more [1]. Because of the often manual manufacturing of composites and maintenance of the used structural parts they have to go through a thorough non-destructive inspection. A commonly used method is an ultrasonic inspection by applying a small single element probe or multiple-element array to scan over the whole testing area. Usually these methods need a water-based couplant, that is not suitable for every kind of material (e.g. foam-like materials or honeycomb structures, which are not water resistant). However, with the increasing use of fiber reinforced components new Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) methods are required to be developed and adapted to these new materials [2, 3]. In the methods where scanning with a single probe is necessary, the scan pattern needs to be fine enough to not oversee any defect and still to provide realistic testing times. A different approach uses the defect-selective resonant methods. Unlike conventional ultrasound, the excitation is not just with a single frequency, but with a sweep through a whole range of frequencies to selectively excite the defects eigenmodes. The frequencies of Local Defect Resonance (LDR) are the frequencies where only defects are locally vibrating [4]. Various methods are available to monitor these local vibrations and use them for imaging of damage (e.g. thermography, scanning



laser vibrometry or shearography) [5-10]. Another LDR-related technique is based on detection of airborne waves radiated by the resonating defects. This Resonant Air-Coupled Emission (RACE) method can be contact free and simply uses an acoustic microphone to detect the acoustic waves emitted locally by the damage [11]. In this paper, RACE imaging of defects is studied by means of different mechanical scanning units (three-axis-scanning table and six-axis industrial robot). A new approach to a full-field RACE imaging is proposed by using a microphone array (acoustic camera). By applying beam forming algorithms to the recorded data of each microphone, the sound of damage is instantly detectable and visualized. Adapting of acoustic cameras to imaging of sound of defects enables to eliminate time-consuming acoustic scanning and to progress in the development of new fully acoustic methods for express NDT and SHM of various materials.

Full-field RACE mode imaging

The results obtained in the experiments above, show that the scanning method visualizing of the defects is useful and provides reasonable RACE imaging. However, this process is rather time consuming. For example, in the robotic experiment the scanning speed was 10mm/s and it took from 10 to 20 minutes to scan the area of the defects. This drawback is avoided in a new full-field RACE imaging method. In this approach an acoustic camera is used for instant detection and imaging of the defect. The feasibility of this technique is demonstrated below using the acoustic camera SoundCam by CAE systems, Gütersloh, Germany, provided by Wölfel GmbH, Würzburg, Germany. It contains 64 MEMS-microphones, the data acquisition system with 24-bit resolution, sample rate 48 kHz with an operating frequency range 10 Hz – 24 kHz. The setup to provide full-field RACE imaging is shown

in the Fig.11. The camera operation included the adjustment of the distance to the sound source, the dynamic range and the frequency of the receiver. To test the acoustic camera operation, the acoustic field of the piezo-actuator (isi-sys) was visualized first (Fig. 12). As one can see from the picture, the active zone of acoustic field of the vacuum attached transducer (diameter 5 mm) is highlighted with a bright spot. This circular spot indicates the position where the sound amplitude is maximal, which matches to the real active zone of the transducer. The SoundCam interface also shown in Fig. 12 indicates reasonably high (> 10 dB) dynamic range of the image and a fundamental frequency radiated (round 13100Hz). The vacuum attached transducer was then used in the noisy mode for the RACE excitation in a PMMA plate with two FBH (Fig. 13). The laser vibrometry test reveals different LDR frequencies for those holes (Fig. 13, a, b). The frequency bandwidth of the SoundCam receiver was then narrowed down around the value of the LDR frequency (12200-13300 Hz, Fig. 13, d) to demonstrate consecutive frequency-selective RACE imaging of the defects.

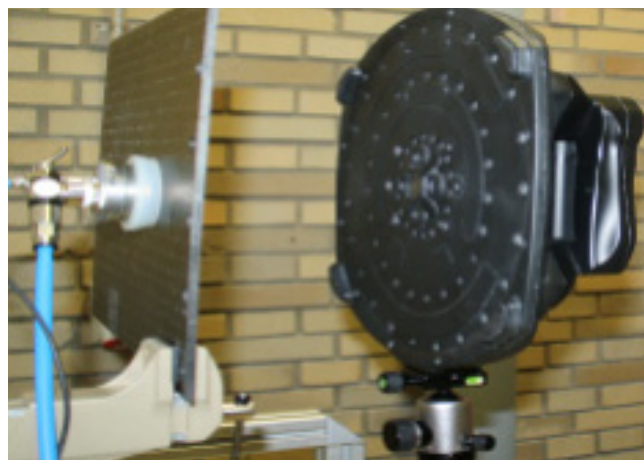


Fig. 11. SoundCam setup for full field RACE imaging

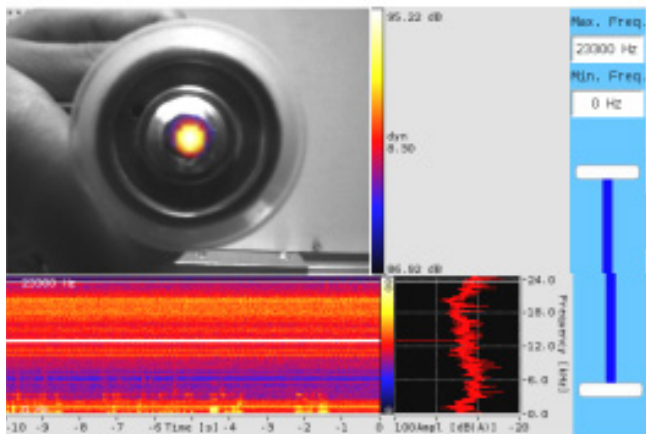


Fig. 12. The interface of SoundCam and full-field image of acoustic filed for isi-sys transducer (frequency 13100 Hz).

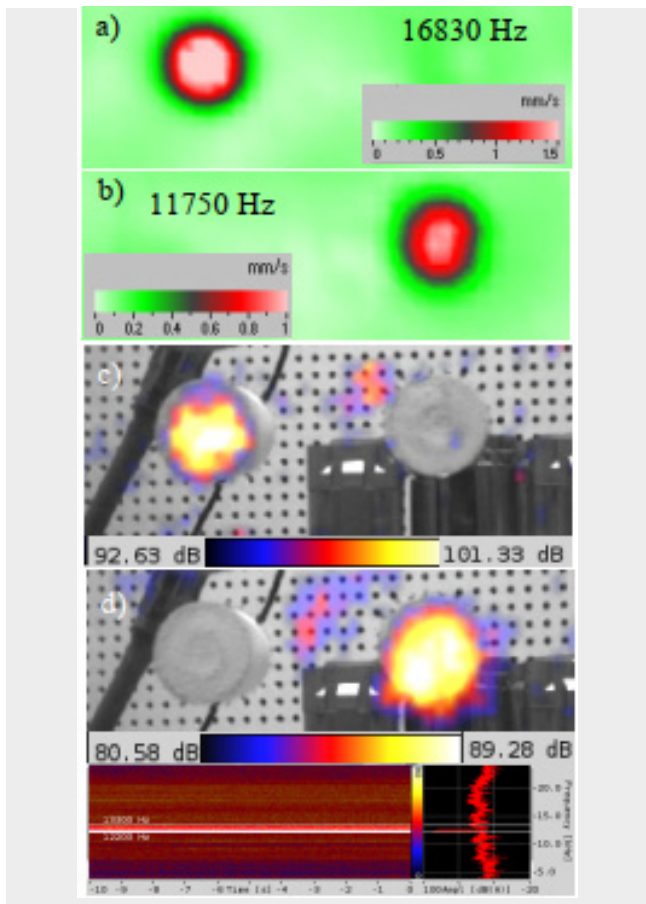


Fig. 13. Frequency selective fullfield RACE imaging (c, d) and laser vibrometry (a, b,) for a pair of circular FBH of different LDR frequencies.

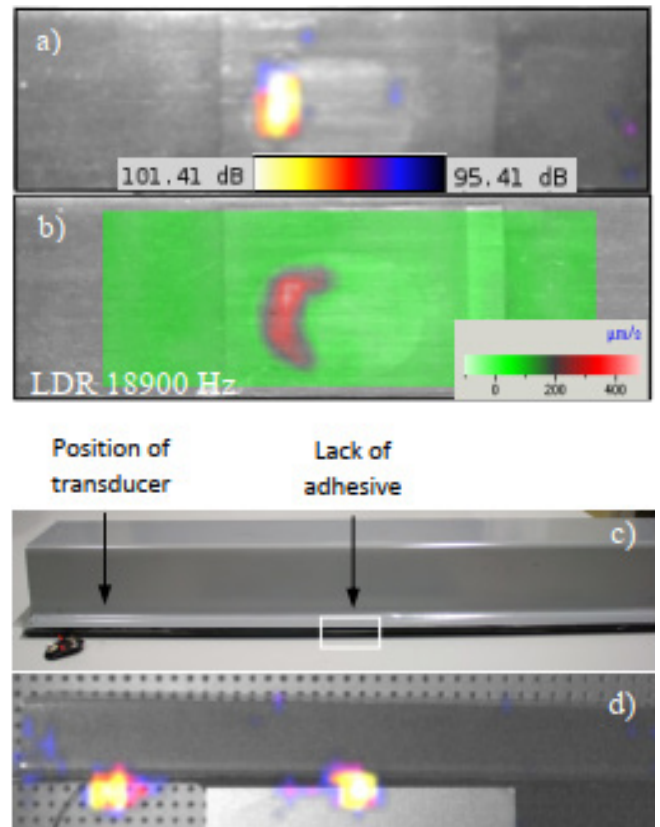


Fig. 14. Soundcam imaging of a delamination in piezo-actuator imbedded in GFRP plate (a), 19800 Hz LDR laser vibrometry image of the delamination; steel profile with adhesive disbond (c) and full-field RACE image of the disbonded area (d).

Full-field scanning can be applied for imaging of not only simulated but also some realistic defects as demonstrated in Figs. 14 a, b, for an elliptic delamination above the actuator imbedded in a Glass Fiber Reinforced Polymer (GFRP) plate.

The active part of the delamination responds to LDR excitation at frequency 18900Hz and is seen in the laser vibrometry scan (Fig.14, b). Full-field RACE excited at this frequency (Fig. 14, a) clearly indicates the resonance part of the delamination but requires much less time for testing. An application of RACE for full-field imaging of defects in a lap joint is shown in Figs. 14, c, d. The joint is made by gluing the flanges of the rectangular steel profile (500 mm x 50 mm x 65 mm³) to 1.5 mm steel base.



The disbond (length ~ 40 mm) is simulated by the lack of adhesive between the flange and the base (inside the white rectangular in Fig. 14, c). A piezoelectric transducer is attached to the base and excited with 20V noise signal. The two bright spots in Fig. 14, d) disclose the acoustic waves generated by the transducer (left) and the RACE field radiated by the disbond area (right).

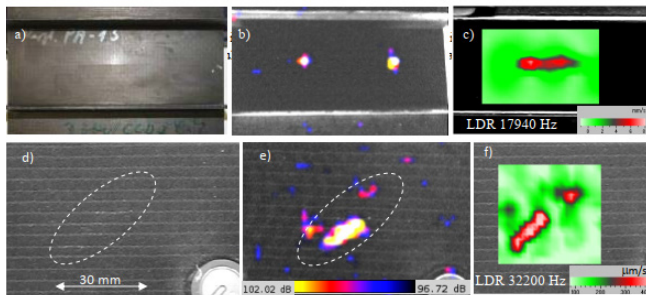


Fig. 15. a) crack in CFRP stringer reinforced sample, SoundCam image (b), laser vibrometer LDR, image (c); d) 20J-impact-induced BVID in non-crimp fabric CFRP plate (d), vibrometry image at fractional LDR frequency 32200 Hz (f) and full field visualisation using acoustic camera (e).

Two other examples of full-field imaging of real impact-induced defects in CFRP are shown in Fig. 15. The impact damage in the stringer-reinforced CFRP plate results in a clearly visible crack on the reverse side (Fig. 15, a) and is closely visualized with laser vibrometry scan at LDR frequency 17940 Hz (Fig. 15, c). Interestingly, that similar to the full field ultrasonic thermography imaging [13], where the vibration of the crack tips leads to the dissipation of energy and the temperature rise, the vibration around the tips area also produces RACE evidently detected by the acoustic camera (Fig. 15, b).

Another impact-induced BVID shown in Fig. 15, d) is a result of 20J-impact in non-crimp fabric CFRP sample (150mm x 100mm x 3mm³). The damage becomes barely visible only because of slight bleaching of the stitching yarn. The laser vibrometry,

nonetheless, reveals the damage most clearly seen at fractional LDR frequency 32200Hz (Fig. 15, f). This value is outside the bandwidth of the SoundCam; for this reason the acoustic camera image in the noisy mode (Fig. 15, e) is obviously not as good as the laser vibrometry scan, however, indicates the presence and the position of the defect.

Conclusions

Study of the RACE features implemented in the paper confirms that the RACE field is produced by the resonant vibrations of a defect (LDR). In the higher kHz frequency range, the RACE field can be readily detected in the transition zone between near- and far-fields that extends well beyond mm-range and precise alignment of the receiver closely to the surface becomes unessential. This enables to apply conventional RACE scanning for imaging of serious defects in composites (including BVID) with modest restrictions on the microphone distance from the defect. Unlike 2D-RACE scanning of flat specimens, the use of industrial robots provides fully autonomous detecting and imaging of the defects in complicated shape components. The robotic RACE scanning combined with wideband noisy excitation proves the feasibility of simultaneous imaging of multiple defects without prior search for LDR frequencies.

A new full-field RACE imaging method with an array of microphones as a receiver avoids the drawback of time-consuming scanning modes and is used for express detection and imaging of defects. The case studies of the full-field RACE mode with acoustic camera array validate reliable imaging of various defects in composites and disbonds in a steel lap joint.