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Nonlinear air-coupled thermosonics for fatigue micro-damage detection and localisation

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ABSTRACT

Over the years, traditional active infrared thermography has played a pivotal role in ensuring that a component is free of any damage. However, whilst optical thermography is still not sufficiently sensitive to the presence of material micro-flaws, current vibro-thermography requires inspection solutions that are not always feasible, such as the use of coupling materials between the sensing probe and the monitored structure. This paper presents a valid alternative to current thermographic systems by developing and experimentally validating nonlinear air-coupled thermosonics for a contactless, rapid and accurate detection of fatigue micro-cracks in an aero-engine turbine blade. The proposed thermographic method combines the high sensitivity to micro-damage of nonlinear ultrasonic techniques with non-contact air-coupled ultrasonic transducers and thermographic equipment. Narrowband frequency sweeps were performed to identify local damage resonance frequencies in order to generate large vibrational amplitudes at the damage location and compensate for signal losses caused by the high acoustic impedance mismatch between the air and the sample. An infrared camera was then used to acquire the thermal response generated by frictional heat at the crack interfaces. Moreover, an image processing method based on a combination of morphological opening and a Savitzky-Golay smoothing filter was employed to enhance the quality of thermal images affected by anisotropic heating and thermal noise effects. Nonlinear air-coupled thermosonics experiments were validated with laser Doppler vibrometry scan measurements and compared with both flash and pulsed phase thermography. Thermal imaging results showed that the proposed nonlinear air-coupled thermosonics was the only thermographic technique able to detect fatigue micro-cracks, thus demonstrating its potential as an efficient and sensitive inspection tool for micro-damage detection in geometrically complex components.

1. Introduction

The ongoing rapid advancements in material science and the resultant increasing use of more complex materials and geometries in engineering design have driven the need for innovation and improvement of current non-destructive evaluation (NDE) techniques. Among NDE inspection methods, thermosonics has gained research momentum owing to its versatility, high testing speed, full-field capability and reduced dependence on the operator [1,2]. Thermosonics (also referred to as vibro-thermography or ultrasonic stimulated thermography or sonic IR) is an active infrared (IR) thermographic method for material micro-damage inspection that involves the generation of powerful vibrations in a test piece to cause frictional heating at crack interfaces [3]. These vibrations are produced by an ultrasonic welding horn being pressed against the surface of the part under inspection. However, the coupling between the test specimen and the horn typically results in an uncontrolled generation of frequency components known as "acoustic chaos". Such a condition makes this method highly non-reproducible, thus leading to cracks being undetected if sufficient vibrational energy is not applied at the crack location. In addition, the exposure to high-power excitation generated by the horn may even further degrade the structural integrity of components [4]. Numerous thermographic strategies and approaches have been developed in recent years to improve the reliability of thermosonics. One of the major technological advances was the combination of nonlinear ultrasonic methods using piezoelectric (PZT) transducers and thermography, which gave rise to nonlinear ultrasonic stimulated thermography (NUST) [5–7]. Nonlinear ultrasonic methods have been gaining increasing popularity due to their high sensitivity to micro-damage (e.g. incipient fatigue cracks) over classical linear methods (e.g. C-scan and linear phased array) [8–12].

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Indeed, linear elastic wave propagation phenomena such as wave scattering and attenuation induced by micro-defects are generally too small to generate wave distortions, so that micro-flaws tend to remain "invisible". Nonlinear ultrasounds, on the other hand, measure material nonlinear effects such as harmonics and sub-harmonics (i.e. multiples and submultiples) of the driving frequency in order to reveal the presence of surface and sub-surface micro-flaws [13]. These effects are mainly caused by the local vibration of micro-cracks, which produces clapping motion and frictional contact between damage surfaces. Since the generation of higher harmonics indicates the presence of damage, they can be used as a signature for a reliable driving frequency selection. The challenge associated with the use of PZT sensors is, however, the question of whether they are capable of injecting sufficient energy into the specimen to produce heat dissipation through friction. This issue has been recently addressed by the analysis of the local defect resonance (LDR) effect. According to the LDR theory [14,15,17], if the driving frequency matches the damage resonance one, the vibrational amplitude of nonlinear elastic phenomena can be dramatically increased by nearly 20–40 dB. Hence, the acoustic interaction between elastic waves travelling through the specimen and the defect can be maximised, thus reducing the input power to a few mW. This enables the PZT transducers to be reliably used as excitation devices. Furthermore, the LDR effect can push the boundary of NUST even further by supporting the implementation of contactless air-coupled transducers (ACTs), thus making NUST a fully non-contact NDE method. Indeed, for practical applications, it is not always possible or feasible to bond transducers and use water or other liquids as the coupling medium between the sensing probe and the monitored structure. A number of studies in literature have shown the feasibility of using non-contact sensing devices and ACTs in both linear and nonlinear ultrasonic applications [18–23]. The use of ultrasounds with air-coupled transducers is known in literature as air-coupled ultrasounds (ACU). Zalameda et al. [24] at NASA firstly used amplified loudspeakers to excite standing waves on a damaged metallic sample and generate frictional heat at the defect location. However, loudspeakers are only able to transmit input pulses at low frequency ranges (typically from ~20 Hz to ~10 kHz), thus limiting the damage detection capabilities to cm-size flaws. To overcome this issue, ACU is proposed in this research, as it allows ultrasonic transmission at higher frequencies to assess material flaws of smaller dimensions. Nevertheless, the use of air as the coupling medium between the transducer and the damaged structure poses major challenges such as high losses in the transmitted signal caused by the severe acoustic impedance mismatch [25]. In this regard, Solodov et al. [26] recently revealed that loudspeakers were able to produce a sound intensity (pressure) of 90 dB at few kHz range on a damaged carbon fibre (CFRP) composite panel with "artificial" cm-size flaws (i.e. flat bottom holes). This level of sound intensity combined with the LDR "amplification" of 25 dB was sufficient to generate standing waves in the sample and frictional contact between damage surfaces, with temperature variations of 30 mK at the defect location. This result opens opportunities for the use of powerful commercial ACTs with thermography that, despite being affected by signal losses in the range of 70–80 dB due to the acoustic mismatch between air and solid, are capable of providing sound intensities of $\sim 10^{-2}$ W/m^2 in materials at frequency ranges broader than loudspeakers [19].

The aim of this study is to develop and experimentally validate a fully non-contact thermal imaging technique, here named as nonlinear air-coupled thermosonics (NACT), for the detection and localisation of fatigue micro-flaws in an aircraft engine turbine blade. The application of nonlinear ACU is particularly relevant as both ultrasonic horns and contact PZT transducers require consistent and reliable contact conditions that are cumbersome to achieve due to the small dimensions and complex geometry of the specimen. Three key aspects of the proposed NACT were investigated in this paper: (i) the optimisation process for the nonlinear ACU transmission, (ii) the accurate selection of the LDR frequency using narrowband sweep excitation and (iii) the enhancement of image processing using morphological opening and a Savitzky-Golay smoothing filter. Moreover, NACT thermal results were validated with two-dimensional (2D) laser Doppler vibrometry scan measurements and compared with traditional thermography. The outline of this research work is as follows: in Section 2 the experimental set-up used to perform experimental NACT tests is presented. Section 3 reports the nonlinear ACU experiments for the identification of the driving frequency based on the nonlinear LDR effect and a modified slanted set-up of ACTs relying on the highest signal-to-noise ratio of measured ultrasonic signals. Section 4 shows the result of NACT tests, whilst Section 5 provides a validation of NACT tests with laser Doppler vibrometry scan measurements. Section 6 provides a comparison with NACT experiments and standard Flash thermography and Pulsed Phase thermography. The conclusions of this paper are finally presented in Section 7.

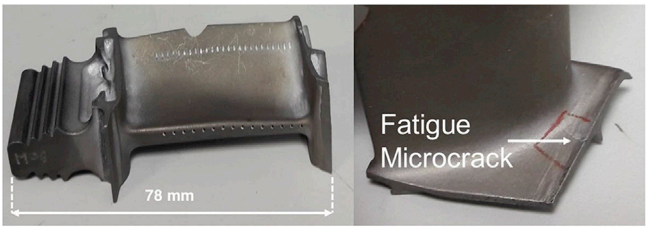

Fig. 1. Inconel aircraft engine turbine blade with a 1.4 mm fatigue micro-crack in its shroud.

2. Experimental set-up

Aircraft engine blades, typically made from titanium and nickel alloys, experience high-cycle fatigue loads due to mechanical vibrations and airflow dynamics in addition to high thermal stresses. Small indentation craters generated by foreign objects can become sites for fatigue micro-crack initiation, thus severely decreasing the lifetime of blades. A 78 mm Inconel aircraft engine turbine blade with a 1.4 mm fatigue micro-flaw in its shroud was selected for testing (Fig. 1). The experimental work included two major elements: nonlinear air coupled ultrasonic tests and thermosonics measurements.

For the nonlinear air-coupled ultrasonic testing, second harmonic was chosen as the nonlinear elastic feature indicating the presence of micro-cracks. A signal generator (TTi TG5011 Function Generator, 50 MHz) was used in conjunction with an amplifier (Ciprian US-TXP-3 High Voltage Power Amplifier) and a transmitting point-focused air-coupled transducer (Ultran ACT NCG50-D25-P76, bandwidth 30–70 kHz) with a central frequency of 50 kHz. The receiving ACT transducer was, instead, chosen with a central frequency of 100 kHz (ACT NCG100-D25-P76, bandwidth 50–150 kHz) in order to provide a higher second harmonic elastic response. The received signal was amplified using a pre-amp (Olympus Panametrics-NDT Ultrasonic Preamp 34 dB), which was fed into a digital oscilloscope (PicoScope 4424) connected to a personal computer. For the calibration of the air-coupled transmission, ultrasonic signals were also recorded using a contactless 2D laser Doppler vibrometry (LDV) system (Polytec PSV-A-420) with a stand-off distance of 507 mm. Signals received by the LDV system were sampled at 1 MHz with an acquisition window $\tau = 2.5$ ms and processed using MATLAB software. Thermography experiments for NACT involved the acquisition of thermal images using a mid-wavelength infrared camera (CEDIP Jade 3 MWIR 3–5 μm, 320 x 250-pixel resolution, average NEDT of 30 mK) with a fixed frame rate of 25 Hz and 56 s recording time (equivalent to 1400 frames). It should be noted that the camera was positioned away from the ACT and was focussed exclusively on the damaged zone without having the ACT included in the video frame. This was to minimise the direct exposure of heat flow from the ACT transducer to the IR camera, which could negatively affect thermal measurements. Additionally, in order to provide a uniform thermal emissivity, the blade was painted black with spray paint. Fig. 2 illustrates the experimental set-up for both nonlinear ultrasonic and thermosonics tests.