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Measuring low-level porosity structures by using a non-destructive terahertz inspection system

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ABSTRACT

It is demanded a non-contact, non-destructive and reliable system and method of porosity measurement because conventional techniques are contact and cubersome. We have developed a method by using THz inspection system, which allows measuring the porosity rapidly and non-invasively, by introducing an external perturbation. The embodiments of the external perturbation can be mechanical or pulsed laser.

1. Introduction

It is always crucial to know the porosity of a manufactured carbon-fiber-reinforced polymer (CFRP) structure in order to determine its suitability for a particular application or whether it meets a product specification [1]. Usually porosity is defined as the ratio of pores or voids in a structure relative to the total volume occupied by the structure.

Porosity measurement is useful in the area where the parts and structures made from composite materials, such as those used in the aerospace industry. Laminated plies of CFRP have wide spread use in commercial and military aircraft. During the manufacturing stage, multiple plies or layers of CFRP are compacted and produced homogenous and rigid structures. In this process voids may left which may reduce the structural strength over the service life of the part [2]. Porosity measurement is also demanded when patching or repairing composite parts since voids can be left along the bondline between the new material of patch and the old material of the structure [3].

Various non-destructive technologies have been utilized to determine the porosity level of the structure. One of the common techniques is liquid penetrant inspection [4]. A chemical is applied to a surface of a structure, allowing the chemical to penetrate into surface recesses, then a solvent or like cleaner/remover chemical is used for removing excess penetrant chemical from the surface of the structure. A detection method is used to identify the location of the penetrant chemical which remains in surface recesses. However, this method is a contact method which is cumbersome, requiring the use of chemical that can pose hazards, the ongoing purchase and disposal of the chemicals. Other common technique for non-destructive inspection includes the use of ultrasonic sound in which a beam of ultrasonic energy is directed into the part whose porosity is measured [5]. Any voids/flaws that may be presented in the structure attenuate/change the sound beam in proportion to the porosity of the structure. The magnitude of the transmitted or reflected signals from the structure is collected by transducer to determine the porosity. However, ultrasonic testing is a contact method, which needs couplants to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected. Therefore, the couplants need to be removed from surface of the structure after measurement, which may introduce contamination on surface of structure. In addition, operation of ultrasonic testing requires careful attention by experienced technicians and extension technical knowledge is required for signal process.

Accordingly, there is a demand for improved non-destructive inspection systems and methods to inspect CFRP structures which may be used instead of conventional non-destructive techniques, devices and methods such as those described above. Here, we develop a method to measure low-porosity structures by using a terahertz (THz) inspection system. The THz waves, which lie between radio waves and infrared waves, exhibit properties of both sides of the electromagnetic spectrum [6,7]. Similar with radio waves, THz can be transmitted through variety of materials, such as composites, ceramics, plastics, resins, wood and foams. Moreover, like light waves, THz can propagate easily through space, reflected, focused and refracted using optics. Thus, THz inspection system has great potential for quality control and it addresses the drawbacks of conventional techniques by providing a rapid, non-destructive, and non-contact technology for measuring the porosity of CFRP structures.

2. Experimental methods

The THz inspection system is based on a THz time-domain spectroscopy (THz-TDS) [8,9]. The system consists of an 800-nm fs

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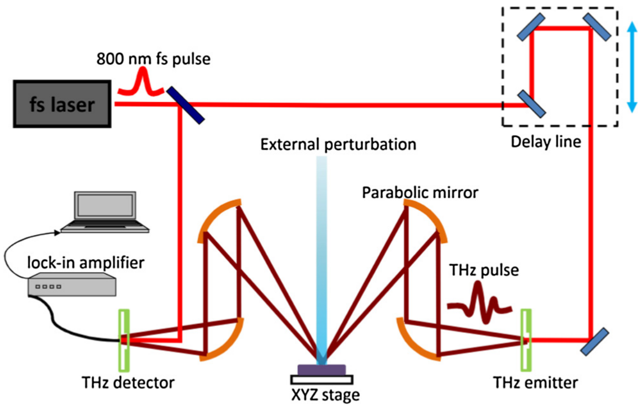

Fig. 1. Schematic of the THz inspection system which porosity of the structures can be measured based on the THz response with and without external perturbation.

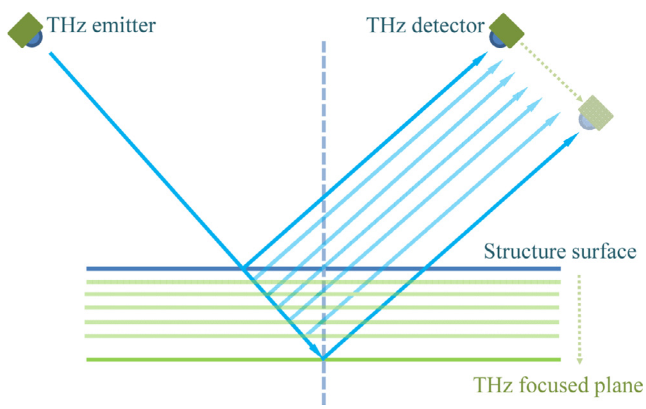

Fig. 2. A pictorial diagram displays the method to gather information inside the structure by changing THz light focused plane.

laser, a THz emitter, an *xyz* scanning stage, a THz detector, a lock-in amplifier, and a computer, as shown in Fig. 1. The THz-TDS can be configured to transmit electromagnetic radiation in THz range toward a surface of structure, received THz light reflected by the structure, and generate a signal indicative of the received radiation. The computer, which communicates with THz-TDS, can be configured to process the generated signal and may further be configured for creating a visual imaging of the THz response from the structure. The *xyz* stage can be configured for holding the structure, scanning the image and move THz focus point to different directions. By tuning the position of the stage (*z* direction of *xyz* stage) THz light can be focused on the surface or inside the structures. By placing THz focus point inside the structure, information regarding pores inside the structure can be recorded by reflected THz light and is useful for further analysis. When focusing THz light inside the structure, it is able to gather more information inside the structure combining with focusing on the surface of structure. The shift of THz focus plane achieved by tuning *z*-axis of *xyz* stage. Fig. 2 is a pictorial diagram of the method. Also, by shifting *x*- and *y*-direction of the *xyz* stage, two dimensional imaging can be obtained. In general, the reflected THz signals of porous samples may be slight different when porosity changes: (1) the variation of refractive index of porous samples [10], (2) THz scattering by pores inside the samples [11]. The study of the propagation an scattering of THz pulses through media has been studied [12–17]. In our application, we are concerned in isolating air bubbles, voids in the material. The scattering of coherent THz radiation $E(\omega)$ can be expressed as following, $\frac{E(\omega)}{E_{inc}(\omega)} = \exp\left[\frac{-z}{2l_s(\omega)}\right]\exp\left[\frac{-\alpha(\omega)z}{2}\right]\frac{4n}{(n+1)^2}$, where $E_{inc}(\omega)$ is the incident THz radiation, $l_s(\omega)$ is scattering mean free path, α is absorption coefficient and z is the thickness of the sample. However, when porosity is extremely low, the above variations are very small. In order to enhance the variation, an external perturbation is employed.

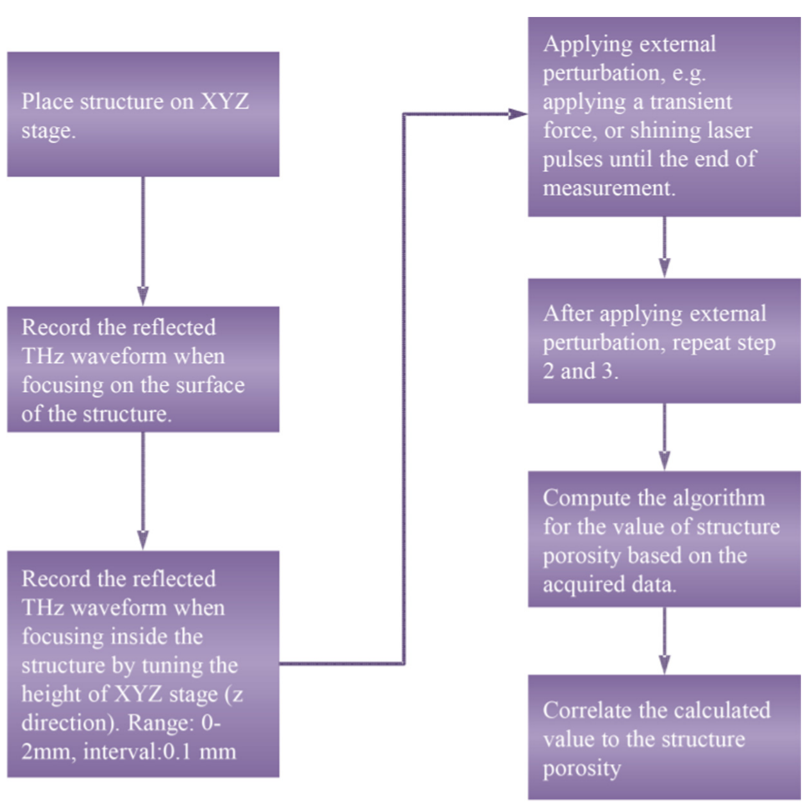

Fig. 3. Exemplary workflow of measuring porosity level by using THz inspection system.