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Quantitative analysis of the influence of voids and delaminations on acoustic attenuation in CFRP composites by the laser-ultrasonic spectroscopy method

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ABSTRACT

The aim of the present work is to develop the ultrasonic spectroscopy method using laser thermoelastic generation and piezoelectric detection of broadband acoustic pulses for quantitative evaluation of the influence on the ultrasonic attenuation coefficient of microscopic dispersed voids and interply delaminations in CFRP laminates. The specimens under study have different entire porosity values up to 10% determined by the X-ray computer tomography. The ultrasonic attenuation resonance is observed in all specimens governed by their periodic layered structure. The absolute maximum and the frequency bandwidth of the resonance peak depend on the total porosity level formed by the predominant type of imperfections, either of only microscopic spheroidal voids entrapped in the epoxy layers or of additional extended interply delaminations. The derived empirical relations between these parameters and the total porosity level can be used for rapid nondestructive evaluation of the structure of CFRP composite laminates subject to different manufacturing conditions.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites are increasingly used as structural components in aircraft constructions due to their high strength and light weight. However because of the two-phased nature of CFRP some structure defects may appear resulting from manufacturing processes of composites, the most common of them is porosity (volume fraction of gas) [1,2]. It is well known that porosity may cause the decrease of the static and the fatigue strength of composite laminates and the increased susceptibility to water penetration and other environmental conditions [3,4]. The whole porosity may be formed by small spheroidal voids entrapped in epoxy layers between fiber plies and extended interply delaminations up to several millimeters in length, but their influence on laminate stiffness, interlaminar shear and residual strength is different [4,5]. Therefore the quantitative nondestructive evaluation of the type and the volume content of such cimperfections and subsequent correlating mechanical and environmental tests of composite specimens are of great scientific and practical importance. The results of these combined studies seem very useful to predict the material behavior during service of the composite products and to evaluate their life time.

Quantitative nondestructive evaluation of porosity in CFRP can be carried out by the X-ray computer tomography, active thermography and a variety of ultrasonic methods – longitudinal ultrasonic wave attenuation and velocity measurements and ultrasonic backscattering measurements [1]. Because of their relative simplicity, safety and high sensitivity to voids and delaminations presence ultrasonic methods are currently the most often used [6,7]. It is well known that porosity strongly affects the attenuation and the velocity of ultrasound since voids are very effective scatterers of elastic waves. Therefore numerous investigations have been carried out to develop techniques that evaluate the CFRP porosity by theoretical calculations and measurements of the attenuation coefficient and the phase velocity of ultrasonic waves propagating in the material (see, for example, [8–14]). But the absolute values of these parameters can be affected in a different way by heterogeneities of different sizes both by small through the whole volume dispersed voids and isolated extended delaminations. This is because of the efficiency of ultrasonic scattering by any imperfection strongly depends on its configuration and on the ratio of its size and the probe ultrasonic wave length [15]. Therefore the spectral analysis technique – ultrasonic spectroscopy [16–19] – is very promising for quantitative characterization of the type and sizes of imperfections in composites. As it was mentioned above the entire porosity in CFRP specimens can be formed by voids with different sizes ranging from tenths of microns to several millimeters. Therefore for quantitative analysis of their influence on the

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acoustic attenuation coefficient or on the phase velocity in composites the investigations should be carried out over a wide ultrasonic frequency band.

Unfortunately the use of conventional piezoelectric techniques for ultrasonic spectroscopy measurements is faced with certain difficulties because of quite low efficiency of the piezoelectric excitation of broadband ultrasonic pulses [20] and with corresponding difficulties in obtaining a uniform frequency response over a wide frequency band. By now considerable work has been carried out with regard to fabrication of efficient broadband piezoceramic and piezopolymer radiating transducers (see, for example, [21–23]). But their design requires some sophisticated mechanical and electrical techniques to inhibit the excitation of natural resonances of a piezoelement to provide the flat response over a wide frequency band. This in turn causes additional losses by the electro-acoustical transformation and leads to the efficiency decrease of the broadband piezoelectric excitation of ultrasound. Besides only the specially manufactured fine-grained piezoceramics and the piezopolymers with high electromechanical coupling coefficients should be used for these broadband transducers.

To avoid these technical difficulties the application of laser ultrasonics [24,25] for CFRP nondestructive evaluation is very promising. The amplitude of laser-induced ultrasonic pulses may reach several hundreds of MPa in the ultrasonic frequency band ranging from tenths of kHz up to hundreds of MHz by absorption of nanosecond pulses of conventional Q-switched lasers with the energy of several mJ. Such powerful and broadband acoustic pulses enable to realize through-transmission or backwall echo ultrasonic spectroscopy methods for CFRP specimens having thickness up to several centimeters. The method of through-transmission wideband spectroscopy with laser-induced ultrasonic pulses and broadband piezoelectric detection was proposed and realized experimentally in the frequency range 1–50 MHz for heterogeneous colloid liquids [26]. This technique was also used to study the influence on ultrasonic attenuation of fatigue-caused structural changes in glass-fiber-reinforced composites in the frequency range 1–20 MHz [27]. Currently the completely remote technique based on laser generation and detection of ultrasound is applied for nondestructive ultrasonic evaluation of CFRP composites [28–30]. The main advantages are the possibilities of testing of complex shaped composite constructions in particular at elevated temperatures. However the interferometric detection of ultrasonic signals in these systems requires some complex equipment for sensitivity enhancement due to the poor specular reflection of laser radiation by a rough surface of composites and completely small amount of reflected light due to a high absorption in CFRP. Therefore at present the sophisticated laser generation and detection systems for remote ultrasonic evaluation of CFRP composites are still quite expensive.

The aim of the present work is the development of the ultrasonic spectroscopy method using laser generation and high-sensitivity piezoelectric detection of broadband acoustic pulses for quantitative evaluation of the influence on ultrasonic attenuation of microscopic spheroidal dispersed voids and isolated extended interply delaminations in CFRP composite laminates. The investigated specimens have different total porosity levels determined by the X-ray computer tomography. The main idea is to study the propagation of the broadband ultrasonic pulses in the layered structure of composites and to analyze the features of the frequency dependencies of the ultrasonic attenuation coefficient in the specimens containing different volume fractions either of isolated dispersed spheroidal voids or of extended interply delaminations.

2. Laser-ultrasonic spectroscopy method

The principle of the broadband acoustic spectroscopy with laser thermoelastic generation of ultrasound is shown in Fig. 1. A laser pulse is absorbed in a special material – the source of ultrasound – that results in the nonstationary heating of the material subsurface layer. Thermal expansion of the laser heated layer produces acoustic pressure resulting in a pulse of longitudinal ultrasonic waves. The amplitude and the temporal profile and consequently the acoustic frequency spectrum of the laser-induced ultrasonic pulse are governed by the temporal intensity profile of the absorbed laser pulse, the thermophysical properties of the absorbing material – the optical absorption coefficient, the volume thermal expansion coefficient, the heat capacity and the thermal conductivity, and acoustic boundary conditions at the absorbing surface [21,22]. With the employment of Q-switched lasers the amplitude of ultrasonic pulses can reach tenths of MPa over a frequency band ranging from hundreds of kHz to hundreds of MHz.

The acoustic pulse induced by laser absorption in the source of ultrasound is the reference ultrasonic pulse in the spectroscopy system and is indicated by the black curve 1 in Fig. 1. After passing through a specimen its profile is changed owing to ultrasonic attenuation (the white curve 2 in Fig. 1) and then it is received by the specially designed broadband piezoelectric detector. Acoustic contacts between the source of ultrasound, the specimen and the detector are provided with layers of a liquid, typically distilled water of the thickness of 1–2 mm. The system is in general analogous to the conventional through-transmission ultrasonic setup except for laser-induced reference ultrasonic pulses.

The amplitude spectrum $S(f)$ of the ultrasonic pulse passed through the studied specimen of the known thickness H is [16]:

$$S(f) = S_0(f)\exp[-\alpha(f)H], \tag{1}$$

where $S_0(f)$ is the amplitude spectrum of the reference ultrasonic pulse measured without the specimen in the acoustic channel, $\alpha(f)$ – the frequency dependence of the attenuation coefficient of longitudinal acoustic waves in the specimen. So the attenuation coefficient as an acoustic frequency function can be determined as

$$\alpha(f) = \frac{1}{H}\ln\frac{S_0(f)}{S(f)}. \tag{2}$$

Dispersion of the phase velocity of longitudinal acoustic waves in the specimen is determined from the measured phase spectra of the reference ultrasonic pulse $\varphi_0(f)$ and that of the pulse passed through the specimen, $\varphi(f)$:

$$C(f) = \frac{2\pi f H}{\varphi(f) - \varphi_0(f)}. \tag{3}$$

The experimental setup of the broadband acoustic spectrometer with the laser source of ultrasound is shown in Fig. 2.

Pulses of the Q-switched Nd:YAG laser operating at its fundamental wavelength of 1064 nm are employed to induce reference pulses of longitudinal acoustic waves in the special source of

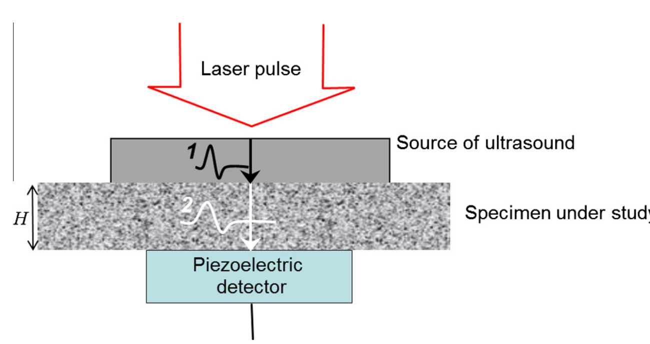

Fig. 1. Principle of the laser-ultrasonic spectroscopy method.