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Near-field microwave identification and quantitative evaluation of liquid ingress in honeycomb sandwich structures

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ABSTRACT

Honeycomb sandwich structures are susceptible to liquid ingress, which causes a serious degradation of performance. Herein, a near-field microwave nondestructive detection technique was proposed to detect, identify, and quantitatively evaluate liquid ingress in honeycomb sandwich structures. Based on the microwave reflection spectrums, liquids of different polarity properties were identified. The amplitude of reflection microwaves was found nearly linear with respect to the height of the intruding liquids in the near field of the coaxial adapter probe. A simple characteristic peak method (CPM) based on line scans was presented and applied to quantify the size of liquid ingress region, and it turned out to be quite accurate with relative errors less than 0.5%. In summary, the near-field microwave testing technique proposed in this study is effective to detect, identify, and quantify liquid ingress in honeycomb sandwich structures.

1. Introduction

Honeycomb sandwich structures are increasingly utilized in the aerospace industry, transportation and civil infrastructures due to their excellent mechanical properties. In general, they are manufactured in the form of a uniform array of hollow hexagonal core cells sandwiched between two adhesively bonded stiff skins [1]. However, such lightweight structures are susceptible to moisture ingress [2–4], which has been proved to be induced by environmental agents, physical damages or chemical factors [5]. The presence of water accumulated in the honeycomb cells does degrade the adhesive between the skin and the core, accelerate the corrosion proceeding, cause unnecessary weight gains [4,6–8], and finally result in structural failure. Besides, honeycomb sandwich structures also suffer from damage due to the ingression and absorption of other liquids, such as hydraulic fluid, kerosene, deicing agent and dichloromethane [5,8,9]. Therefore, there is a great need to detect and evaluate ingress of different liquids inside honeycomb structures.

Currently several methods have been proved available to detect the presence of water ingress inside honeycomb structures, such as ultrasonic [10,11], X-ray [12] and thermography [13–15] techniques. However, ultrasonic signal suffers great attenuation in through-thickness direction of honeycomb sandwiches and commonly coupling agent is needed, while X-ray is hardly used in situ and requires strict safety precautions. Thermography, though fast and efficient, is susceptible to environmental variations and mainly used to initially screen honeycomb structures. A magnetic resonance approach has also been investigated to detect the presence of water within honeycomb sandwich panels [16–18], but it claimed time-consuming and the spatial resolution and sensitivity of the measurement were limited. Overall, these techniques all suffer from certain limitations and they are mainly focused on water ingress. Very few investigations have been undertaken to identify and quantitatively evaluate different liquids intruding inside honeycomb cells.

On the other hand, there is a promising nondestructive method using microwave. The inherent properties of microwave, such as high frequency, good penetration, non-ionization and high sensitivity to polar molecular [19–21], make it well-suited to detect honeycomb sandwich structures. Impact damage in carbon fiber polymer specimens was detected using millimeter-wave reflection [22]. In Ref. [23], a moisture sponge on the back surface of the radome panel was detected from the front, which demonstrated the ability of microwaves to detect moisture intrusion. Unfortunately, little quantification was done further. Therefore, it is essential and interesting to further expand this technique in the identification and quantitative evaluation of different liquids ingress in honeycomb sandwiches.

In this study, a near-field microwave nondestructive testing system is constructed to detect, identify, and quantify different liquids trapped in honeycomb core cells. Microwave reflection

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spectrums of different liquids were obtained, and they were used to identify the type of the intruding liquid. Magnitude of S11 was found to be nearly linear with respect to the height of intruding liquids in the near field. In addition, a novel and simple method of CPM was proposed and proved feasible to accurately determine the size of liquid ingress region with super-resolution.

2. Experimental procedure

A near-field microwave detection system was set up in this study, which consisted of a computer, an Agilent Technologies E8363C phasor network analyzer (PNA), a coaxial adapter probe, and a three-dimensional mechanical scanning stage. A photograph and schematic of the system are shown in Fig. 1(a) and (b). The full operating frequency band of the PNA was from 10 MHz to 40 GHz, and the wideband adapter probe was available in the range of DC-40 GHz. The PNA was controlled by the computer to generate microwaves and receive echo signals. The scanning stage was driven to perform one-dimensional or two-dimensional scan according to programs in the horizontal direction, and in vertical it was adjusted to set the specimen surface in the vicinity of the end of the coaxial adapter probe at a distance much smaller than the operating wavelength. The near-field wideband coaxial adapter probe was employed to transmit and receive microwave signals. A 200 mm (width) × 200 mm (length) honeycomb sandwich panel was fixed on the scanning stage with top skin removed, for the convenience of liquid injecting. The amplitude and phase of reflected microwaves varied with dielectric properties distribution inside the specimen. Liquid ingress could be detected and identified from normal regions according to abnormities in the reflected microwave signals.

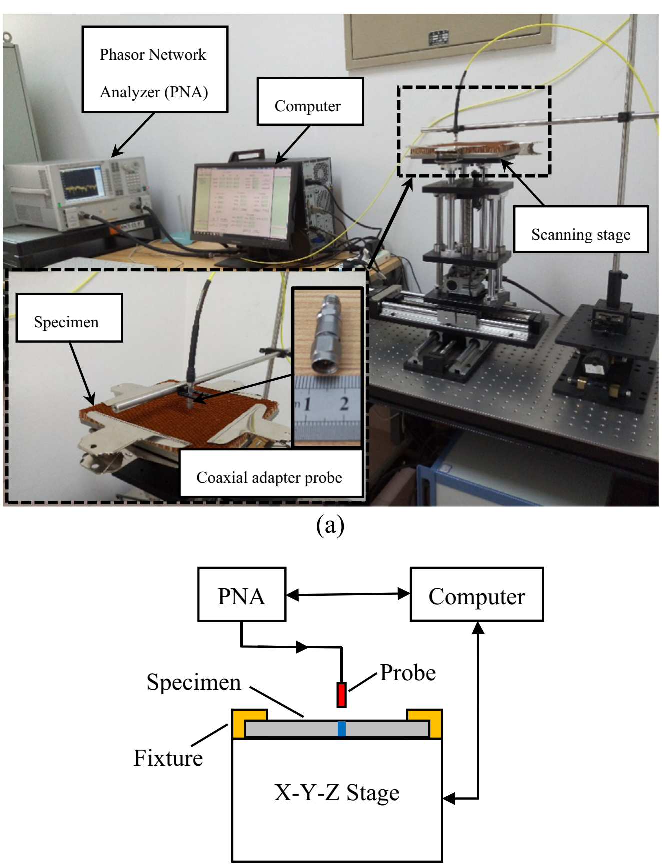

Fig. 1. Near-field microwave detection system: (a) photograph, (b) schematic.

This study was conducted on a Nomex honeycomb-cored sandwich panel with glass fiber-reinforced epoxy skins. The thicknesses of the skin and the core were 1.0 mm and 10.0 m, respectively. The wall of the hexagonal core was 0.1 mm in thickness and 3.0 mm in side length. Water, ethyl alcohol (mass fraction no less than 99.7%) and lubricant oil were employed and intentionally injected into the honeycomb cores with different amounts and in different regions. The standoff distance between the end of the probe and the top surface of the core layer was set constantly as 0.5 mm during measurements and line scans.

3. Results and discussion

3.1. Identification of water, alcohol and lubricant oil

In order to detect and identify different liquids trapped in the honeycomb core cells, a preliminary investigation was conducted based on reflection spectrums. Frequency-sweeping was performed separately over water, ethyl alcohol, and lubricant oil, and reflection spectrums in the range of 32–40 GHz were plotted in Fig. 2(a). For comparison, an empty case without liquid in the holder was also considered. The reflection coefficients of water,

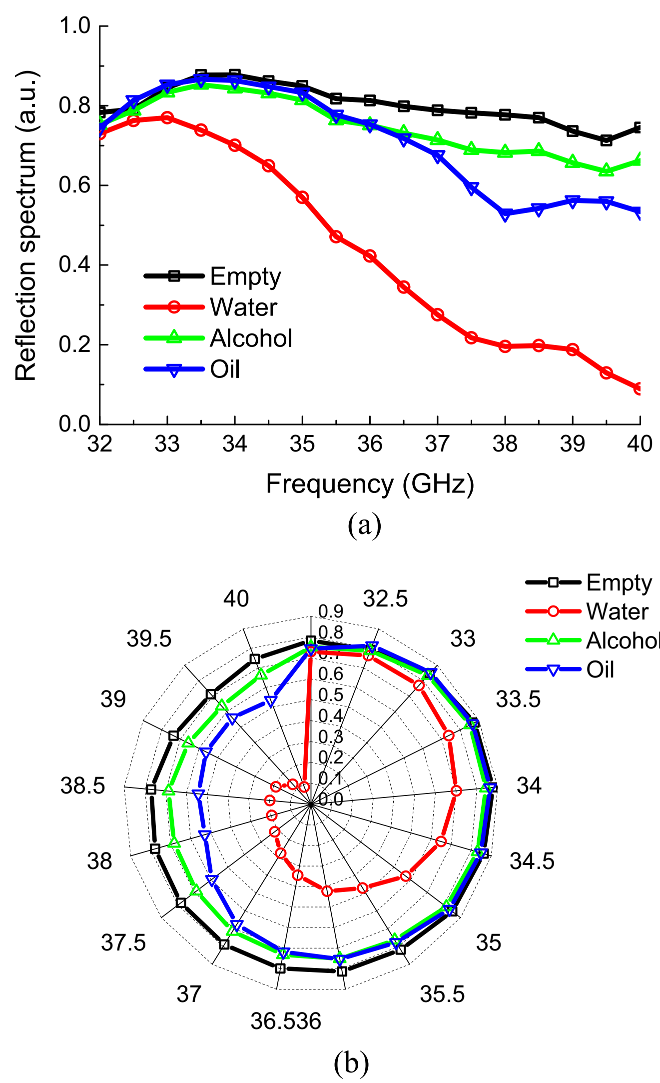

Fig. 2. Reflection spectrums in the sensitive range of 32–40 GHz: (a) in normal form, (b) in the form of radar map.