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Analysis Method

# Nondestructive examination of polymethacrylimide composite structures with terahertz time-domain spectroscopy

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ABSTRACT

THz reflective time domain spectroscopy (THz-RTDS) has been considered as an effective method to detect hidden objects with potential for supplementing other NDE technologies for foam composite adhesive structure debonding defects. PMI (Polymethacrylimide) is a heat-resistant foam material, with the highest strength and stiffness to weight ratio. It is widely used in various parts of airplanes, especially the wing leading edge and rudder, landing gear doors, wing-body/wingtip fairings and so on. We analyzed the features of adhesive debonding defect based mainly on the variation of the time-domain wave form and compared with the inclusion defect. The quantification of degrees of adhesive debonding can be readily achieved with THz-RTDS images based on the delay of the wave front and the main reflection time-domain waveforms. Typical accuracy of about 100 μm was achieved.



## 1. Introduction

As the core material for sandwich structures, Polymethacrylimide (PMI) foam is widely used in the wing leading edge and rudder, landing gear doors, wing-body/wingtip fairings of airplanes. PMI is a heat-resistant foam material, with the highest strength and stiffness to weight ratio. With the increasingly wide application of PMI foam materials, the demand for its quality control and nondestructive testing, inspection, and evaluation (NDT/NDI/NDE) is also increasing. Foam sandwich structures may be damaged by various factors during manufacturing and in deployment. In addition, other defects, such as voids, inclusions, cracks, adhesive debonding, etc., will also present safety risks in the process of practical applications of such structures.

Unlike other composite materials, due to the foam material's unique sonic and optical properties, i.e., its strong sound attenuation and near unity index of refraction, traditional NDE techniques such as ultrasound and optical/microwave based approached are not useful. Likewise, x-ray imaging is ineffective due to its lack of contrast, and it is difficult to clearly image defects such as voids, cracks, and mixed varieties., Compared with electromagnetic wave in other frequency bands, THz wave, in the detection of the foam composite material, has many unique features. For example, in such materials THz wave scattering is relatively small; spatial resolution is higher than that of microwave; and THz is much safer than X-ray, due to its very low photon energy [1]. On the other hand, THz wave are almost translucent for these materials, so it can easily realize NDE of foam material, help evaluate coating quality, debonding and coating thickness. In fact, THz NDE technology can be a useful complementary technology to Fourier infrared spectroscopy (FIS), ultrasound, and X-ray based NDT technologies [1].

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THz time domain spectroscopy (TDS) has been shown to be a very effective method for THz detection and imaging [1]. THz-TDS technology is a coherent detection technology, which uses the THz sample transmission or reflection spectrum to obtain the amplitude and phase information of the THz pulse. Zhang et al., have designed and built a portable continuous wave THz imaging system, which has been approved by NASA for the detection of the space shuttle foam insulation.[2,3] In 2012, Roth et al. used THz computed tomography (CT) NDE to analyze the voids and impact damage of thermal protection system of the space shuttle's external fuel tank. A comparative analysis is made with the micro focused X-ray tomography. The results showed that the NDE effects of 10–50 mm defects were better than that of X-ray. THz can be employed as a more precise and safer method than X-rays [4,5].

However, thus far studies of THz detection of objects buried in foam materials were limited to polyurethane foam. Due to performance issues, from a practical point of view, currently in many areas the polyurethane foam sandwich structures have been replaced by PMI foam structures. To date little has been done in terms of THz NDE of the latter material. In this paper, we test PMI foam with adhesive debonding structure using the reflective THz TDS system, to demonstrate its capability of NDE. In particular, the imaging, clear identification, and quantification of degrees of adhesive debonding can be readily achieved with THz NDE. Imaging by the debonding features that the time-domain wave changes in front of the main reflection, we can distinguish the debonding degrees (from about 0.1 mm to 3 mm) clearly. In this experiment, a paper inclusion simulated defect with 0.0665 mm thickness was also successfully identified by time and frequency domain imaging.

The remainder of this paper is organized as follows. In Section 2, the THz TDS imaging system and the samples used in our experiments are briefly introduced. Section 3 describes the related theories of refractive index and the imaging algorithm. The experimental results and analyses are given, and the effectiveness of the proposed method on PMI testing is shown and discussed through experimental results in Section 4. Finally, conclusions are presented in Section 5.

## 2. THz TDS imaging system description and samples preparation

This experiment is based on the API THz-TDS system T-Gauge 5000. Fig. 1 shows a schematic diagram of the THz TDS system in the reflection mode. The THz-TDS pulse is excited with a Ti: Sapphire oscillator, which produces 1064 nm central wavelength pulses, 80 fs duration, and 100 MHz repetition rate, with a 20 mW average power. In the reflection mode, the transmitter and receiver are coupled with a collinear adapter to perform as a collinear reflection transceiver.

### 2.1. The THz-TDS imaging system

The main specifications of the system are as follows: a spectrum range of 0.1–3.5 THz with a spectrum resolution of 12.5 GHz, a signal to noise ratio better than 70 dB at the lower frequency beginning, and about 30 dB at the high-frequency end, an observation window range of 0–80 ps, with 0.1 ps resolution, and a rapid scanning rate of 1 kHz, and a focal spot of 1.2 cm in diameter. The raster scan minimum step size is 0.1 mm and the imaging area of the XY-stage is up to 30 $\times$ 30 cm.

As a general form of NDE, we mainly use the THz reflection mode TDS (THz-RTDS). Fig. 2 shows two reflection detection modes, both of vertical incidences. The focal length is 3 inches. In the detection process, the substrate is placed at the focal point of the detector to detect the reference signal, followed by the sample signal detection. In order to remove the effects of background noise and improve the detection signal stability, we used multiple measurements averaged to obtain reliable detection signal.

### 2.2. Sample preparation

Before the experiment, the most critical task is to find out the examination requirements of the material. For inspecting any material, the prerequisite is an understanding of the nature of the key defects which cause intolerable performance of the materials [6]. Such defects will pose a safety threat, when these materials are used in aviation, aerospace, and other fields, sometimes even a catastrophe [6].

In this study, PMI foam samples with different defects that may occur in the process of actual production or deployment are prepared for investigation [5–7] with THz-RTDS. The sample is constructed from PMI material Evonik Degussa ROHACELL 71WF, with thickness of 35.02 mm. The sample defects are adhesive debonding and inclusions. The corresponding degree of adhesive debonding at the worst location is 1.2 mm. The adhesive debonding defect was obtained using the SJ-2A (a thick non porous honeycomb structure

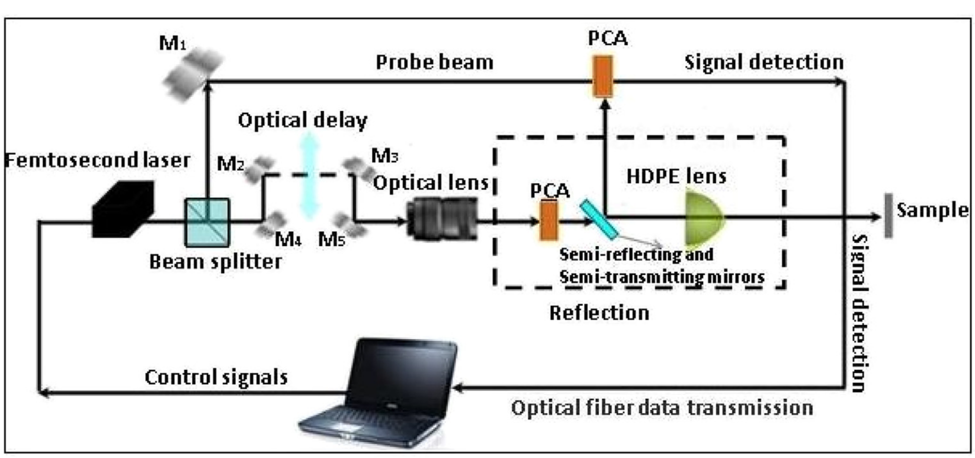


**Fig. 1.** Schematic diagram of the THz-TDS system in the reflection mode (M1~M5: mirrors; HDPE: high-density polyethylene. PCA: photoconductive antenna.).