Rapid Time Domain Terahertz Axial Computed Tomography for Aerospace Non-Destructive Evaluation

David Zimdars[a], Greg Fichter[a] and Artur Chernovsky[a]
[a]Picometrix LLC, Ann Arbor, MI 48104 USA

***Abstract*—A rapid time domain terahertz computed axial tomography (CT-TD-THz) system is described. The system is used to reconstruct three dimensional structure of aerospace components including: Kevlar soft shell fan containment systems, silica thermal protection tiles, and sprayed on foam thermal insulation.**

I. Introduction And Background

Time domain terahertz (TD-THz) non destructive evaluation (NDE) imaging has been demonstrated as a useful sub-surface inspection method for aerospace materials such as non-conductive polymer matrix composites; and polymer, ceramic, and silica thermal protection materials[1]. Conventional TD-THz reflection imaging utilizes the sub-picosecond near single electromagnetic pulses to generate images in a non-contact analog to pulsed ultrasound inspection. TD-THz reflection images are typically presented as either "B-Scans" which represent the cross-sectional laminography of the object, and/or "C-Scans" which represent a two dimensional (2D) radiographic view.

The potential for TD-THz to generate 3D representations of the interior of objects has the potential to be of great utility to aerospace NDE. While TD-THz reflection tomographic "B-Scans" are a 3D representation of an object, they have several limitations. These limitations include: ambiguity of the geometry and internal dimensions due to varying index of refraction; the necessity of sufficient index change between layers in order to generate a reflection; and the necessity that the layer reflection be nearly specular. Furthermore, the inherent 3D information in a transmission image is even less; limited to the time of flight of the pulse, which is related to the amount of material at each point in the object.

Computed axial TD-THz tomography (CT-TD-THz) has the potential to overcome several of these limitations inherent in TD-THz reflection tomography. Previously, Wang and Zhang have demonstrated CT-TD-THz on small objects such as a tennis ball and a bone[2]. In the current work we demonstrate a rapid CT-TD-THz system to reveal the 3D structure and internal flaws of larger aerospace structures such as Kevlar soft shell fan containment systems, silica thermal protection tiles, and sprayed on foam thermal insulation.

II. Results

A Picometrix T-Ray™ 4000 fiber optic coupled TD-THz instrumentation platform was configured as a transmission CT-TD-THz test bed, shown in the photograph in Fig. 1. On the left in Fig. 1 is the TD-THz transmission CT gantry with mounted SOFI foam "P" test phantom (see Fig. 3); fiber pigtailed TD-THz transmitter and receiver modules; and confocal focusing optics. On the right in Fig. 1. is the 19 in. rack mountable T-Ray™ 4000 fiber coupled control unit and display.

Three automated motion axes which served the CT gantry: a rotation stage to rotate the object under test through the axial angle θ, a linear axis to move the object through chord axis d, and an orthogonal linear axis to move the object through slice depth axis z. A THz transmitter and receiver pair are configured with HDPE lens focusing optics with 175 mm F.L. The maximum object diameter is approximately 30 cm. While currently the object is moved by the gantry, the gantry can be configured to move the fiber optic coupled sensors axially around a static object.

Fig. 1 Time domain terahertz transmission computed tomography (CT-TD-THz) setup.

Sinograms are generated using data acquisition software in control of the gantry. Waveforms are recorded for each step in angle θ and chord d. The waveforms are analyzed by computing values such as the power integration over a frequency range, or the time of flight of the pulse. These scalars are the values for each point in sinogram, analogous to the radiodensity in an X-Ray sinogram. 2D cross sectional slice images are reconstructed using filtered back projection and an inverse Radon transform algorithm. Multiple sinograms are acquired by stepping the object on the z axis.

A single THz transmitter-receiver pair was used. The instrument collects a 320 ps window at 100 Hz. One full rotation of 360 degrees requires about 4 seconds. A single slice with 100 cross-sectional chords in the d axis takes about 6 minutes. Data acquisition time for a single slice is roughly equivalent to that required for a conventional 2D raster scan. The scan time is inversely proportional to the number of transmitters and receivers channels.

The qualitative and quantitative interpretation of the value of a voxel in a reconstruction depends on the method to

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compute the scalar value for the sinogram from the TD-THz waveform. In an extinction CT-TD-THz reconstruction, the extinction (absorbance) is calculated over the path between the transmitter and receiver by taking the logarithm of the power transmitted between a range of THz frequencies. The resultant voxels in the reconstruction are extinction coefficients for the material (scaled to the voxel length) In an index CT-TD-THz reconstruction, the difference between the time-of-flight of the pulse in air and the time of flight of the pulse is calculated for each point in the sinogram. The resultant voxels are group index of refraction values for the material within the voxel. The hyper-wideband nature of the TD-THz pulse and the ability to calculate both the extinction coefficient and index at each frequency within the pulse allows for potentially even richer analysis than dual energy X-Ray CT (without the cost of extra sources and/or detectors).

Fig. 2 shows the CT-THz extinction reconstruction and sinogram of a polyethylene test object, approx. 1 cm x 3 cm with a 0.5 cm slot. The sinogram values are proportional to the log of the total THz power transmitted from 0.3 to 1 THz The pixel value of the reconstructed image should then be proportional to a differential extinction coefficient of the material (analogous to the radiodensity in X-Ray CT). The interior of the rendered object is of similar brightness as the air, which is reasonable as HDPE has a low extinction coefficient in the THz spectrum. The surface of the object is dark, representing the Fresnel reflection loss of the surface, which in the reconstruction renders the object in outline. In X-Ray CT, surface voxels are often suffer from an artifact called the partial volume effect, where the value is an (indeterminate) average of the two media at the interface. Extinction CT-TD-THz images combine both the partial volume effect with the Fresnel surface loss. The Fresnel outline is both fortuitous on the one hand, since otherwise the contrast would be lower; but on the other hand the extinction coefficient of the surface voxels is not quantitative.

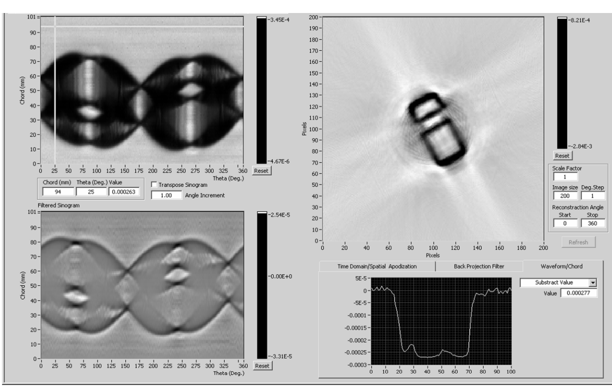

Fig. 2 Extinction CT-TD-THz image. Raw sinogram, filtered sinogram, and 2D slice cross section of a polymer rod intersecting a through hole.

Index CT-TD-THz images were made on a sprayed on foam insulation (SOFI) test phantom made of the polyurethane foam which is sprayed onto the space shuttle external tank.

A close-up photograph of a (SOFI) test phantom is shown in Fig. 3. The SOFI phantom is approx 3.5 in x 3.5 in square by 5 in. deep. A 0.5 in wide "P" has been slotted in the foam. Foam has been removed to a depth of 1 in for entire P and 2 in. for the bottom part of the P. A 0.25 in diam. hole has been drilled to a depth o 3 in The phantom was constructed to both have straight lines and curves, small land large features, and features at several different depths.

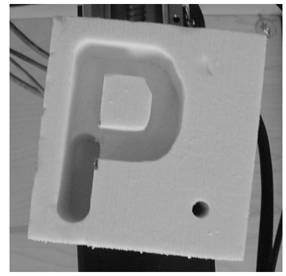

Fig. 3 Close-up of SOFI foam test phantom. .

The delta time-of-flight filtered sinogram of the SOFI P test phantom at 0.5 in depth is shown in Fig. 4. The value of each point in the sinogram was computed by calculating the time of flight of the pulse through the foam referenced to air after applying a 2 pole high pass filter at 400 GHz. Due to the very low index of the foam, the maximal excess delay over air was only about 3 ps.

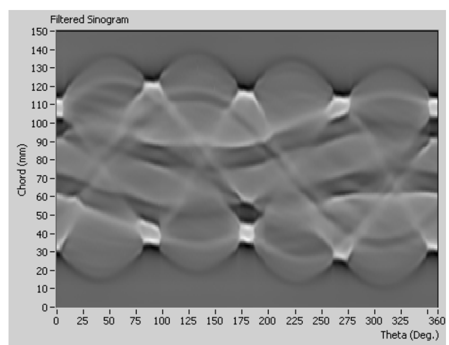

Fig. 4 Close-up of SOFI foam test phantom. .

A summary montage of the index CT-TD-THz reconstructions of the SOFI P test phantom is shown in Fig. 5. The intensity of the pixels is proportional to the excess time of flight (related to the index of refraction) in the foam (white) vs. air (black). White/gray pixels have the index of refraction of the foam (~1.02-1.10). Note that the index reconstruction is free from the Fresnel surface artifact, and an many ways gives results more similar to the "extinction" X-Ray CT method (there being no direct index analog in X-Ray CT).

The TD-THz beam was imaged through the foam using the standard confocal TD-THz lens system with focal length of approx. 175 mm. Although the beam is not perfectly collimated throughout the width of the sample (as an X-Ray

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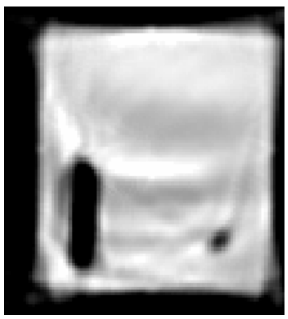
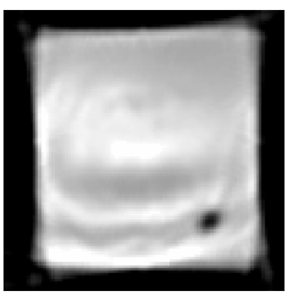
beam would be), the reconstruction worked very well and was not significantly distorted by the non-collimated beam. The effect of the non-collimated beam appears to be the loss of some resolution (effectively larger) voxels at the edge of the object (if the focus is in the center).

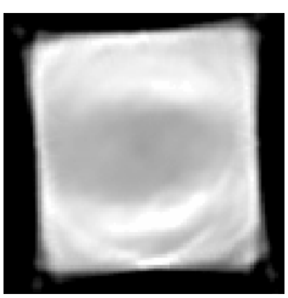
0.5 in deep



1.5 in deep



2.5 in. deep



3.5 in. deep

Fig. 5 Index CT-TD-THz reconstructions of SOFI "P" test Phantom shown in Fig. 3.

A photograph and index CT-TD-THz reconstruction of a torn Kevlar cloth wrapped over a 150 mm diam tube is shown in Fig. 6 The polyethylene tube provided a convenient round substrate for the Kevlar. The Kevlar was cut and torn in a 2 in. long swath. The TD-THz slice was taken so as to cross-section the Kevlar with rip (on the right of the reconstruction). The Kevlar cloth and tear is visible as it separates from the substrate.

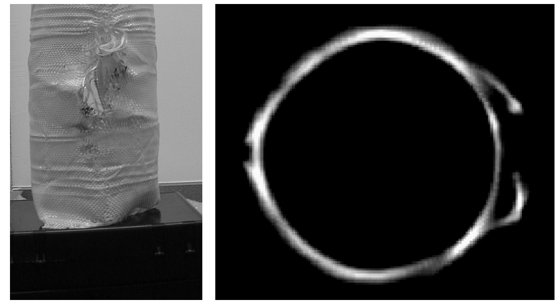


Fig. 6 Photograph and index CT-TD-THz reconstruction of torn Kevlar cloth wrapped on a 150 mm diam polyethylene tube.

A photograph of a space shuttle silica thermal protection system tile (TPS) is shown Fig. 7, left. The index CT-TD-THz reconstruction of the tile is shown in Fig.7, right Qualitatively, the reconstruction has a similar shape to the tile. The tile was approx 10 in long, and the reconstruction appears to be slightly distorted by the confocal THz beam for this larger object (in comparison to the SOFI "P" cube previously). The higher density ceramic coating (black in photograph of tile) corresponds to the brighter pixels in the reconstruction image on the surface of the convex curve.

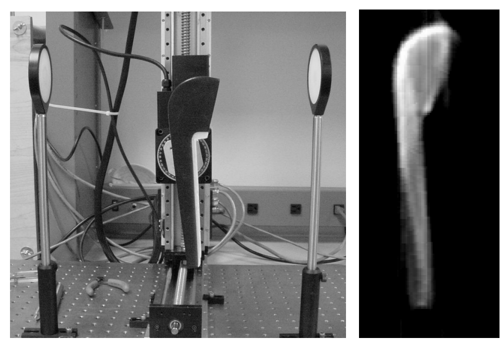


Fig. 7 Photograph and index CT-TD-THz reconstruction of a space shuttle silica thermal protections system tile.

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