Evaluation of holographic subsurface radar for NDE of space shuttle thermal protection tiles

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ABSTRACT

Experiments have been carried out to evaluate holographic subsurface radar (RASCAN) for non-destructive evaluation (NDE) of subnominal bond conditions between the Space Shuttle Thermal Protection System tiles and the aluminum substrate. Initial results have shown detection of small voids and spots of moisture between Space Shuttle thermal protection tiles and underlying aluminum substrate. The characteristic feature of this device is the ability to obtain one-sided radar soundings/images with high sensitivity (detecting of wire of 20 micron and less in diameter), and high resolution (2 cm lateral resolution) in the frequency band of 3.6-4.0 GHz. JPL's advanced high-speed image processing and pattern recognition algorithms can be used to process the data generated by the holographic radar and automatically detect and measure the defects. Combining JPL's technologies with the briefcase size, portable RASCAN system will produce a simple and fully automated scanner capable of inspecting dielectric heat shielding materials or other spacecraft structures for cracks, voids, inclusions, delamination, debonding, etc.. We believe this technology holds promise to significantly enhance the safety of the Space Shuttle and the future CEV and other space exploration missions.

Keywords: Holographic radar, non-destructive testing, space shuttle thermal protection tile bonding.

1. INTRODUCTION

The disastrous loss of the Space Shuttle Columbia, as well as even more recent dangerous incidents that were thankfully resolved, have aroused interest in possible new methods and devices for non-destructive testing and evaluation of the Space Shuttle Thermal Protection System, the external fuel tank insulating foam, and other materials and structures on the shuttle (see **Figure 1**), and possible new space vehicles. Voids in or under the external tank insulating foam are considered potential sites for "cryopumping" where water seeps in and then

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evaporates explosively at altitude, pulling the foam from the tank (**Figure 2**).

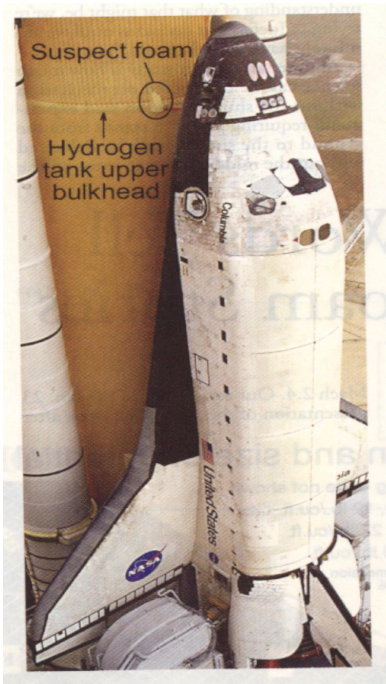


Figure 1. Suspect flaws on the external hydrogen tank coating [1].

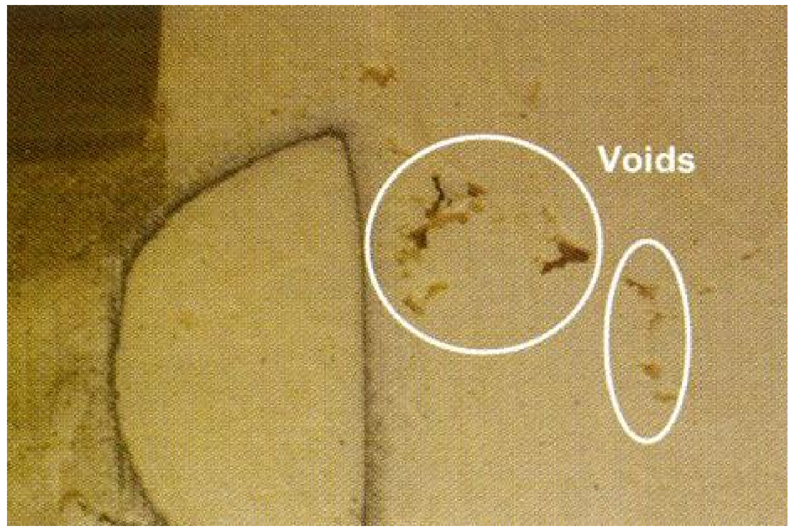


Figure 2. Close-up of voids in the external tank insulating foam [2].

During summer 2003, structures work along the wing/fuselage mate rivet line on Orbiter Vehicle 105, Endeavor, forced the removal of several tiles for rivet inspection and replacement. During the removals several tiles were identified to have a subonominal bond between the tile and the Strain Isolator Pad (SIP). This was an unusual subnominal bond for the TPS as it had never been identified in the past.

The only way to evaluate the tiles was to remove them nondestructively, so they could be reused, by skiving through the SIP from an adjacent tile cavity. The half of the SIP that remains attached to the tile is typically removed by cutting through the SIP/Tile bond line (Refer to Figure 3). During that SIP removal process, technicians noted the SIP and Room Temperature Vulcanizing (RTV) was peeling adhesively from the Inner Mold Line (IML) on the surface of the tile shown in Figure 4. An adhesive peel, is considered a subnominal bond condition, and is referred to as a subnominal SIP/IML adhesive bond. A nominal SIP to tile bond should have a coat of red RTV on the surface of the tile once the SIP is removed as shown in Figure 5.

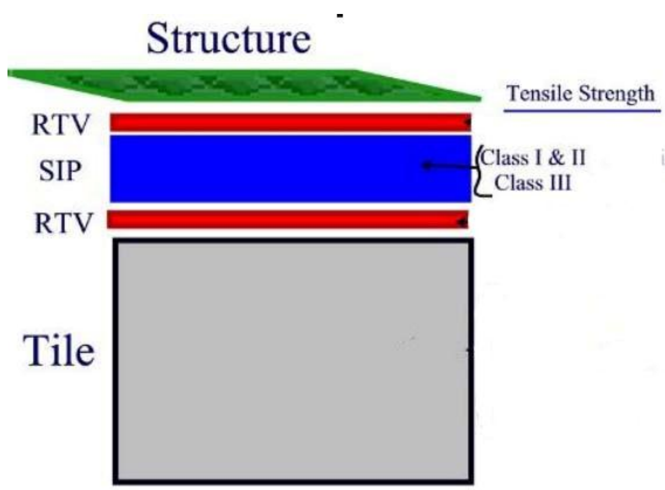


Figure 3: Cross Section of Tile Adhesion with Tensile Strength

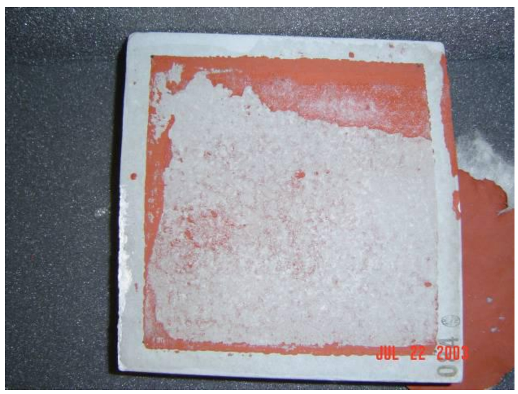


Figure 4: Tile Subnominal Bond Condition

Figure 5: Nominal SIP to Tile Bond Condition

These are the types of conditions which, if they could be detected, would save many hours worth of work removing and replacing tiles on the Space Shuttle Orbiter. In addition, detection of voids between the RTV and the structure of the vehicle would allow for a higher confidence in the tile bond overall[8].

Existing methods of NDE of structural and building materials or components have a number of disadvantages. X-ray devices, for example, require two-sided access to the test subject. This is often complicated and sometimes impossible. Ultrasonic equipment has proven to be ineffective in media containing a great number of micro cracks and heterogeneities. From this point of view, microwave devices are the most promising as they make possible the use of reflective sounding; i.e. transmission and reception of electromagnetic waves is performed from one side of the sounded surface. Up to now, the use of radar for NDE has been hindered by insufficient resolution of available subsurface radars. The impulse radar suffers from low resolution and sensitivity in the dielectric materials on metal substrates. The Terahertz imaging can only penetrate millimeter depth.

The holographic radar, on the other hand, uses a continuous wave (as opposed to impulse), multi-frequency radar signal. It is a reflection mode radar (i.e. the transmitting and receiving parts of the antenna are located on the same side of the sounded surface). The subsurface images are generated as a plan-view holograph rather than as travel time cross-sections as in impulse radar. The holographic radar system operates in frequency range of 3.6 through 4.0 GHz, and uses 5 working frequencies at two receiver polarizations each [3]. Its technology has found application for NDE of building structures and works [6], and humanitarian demining [5].

2. PRINCIPLE OF HOLOGRAPHIC RADAR

The holographic subsurface radar uses a small diameter scanning aperture antenna (**Figure 6**) that produces un-modulated, multi-frequency signals. The signal is received in two orthogonal polarizations at each of five operational frequencies – simultaneously producing 10 images with varying sensitivity to features with differing depth, dimensions, and dielectric contrast. Optical analogy of radar operational principle is presented in **Figure 7**. The raw microwave images that are produced in real time during scanning already possess high resolution in the plane of the surface that is scanned. However, the coincident images can be post-processed and synthesized with specialized algorithms that improve the resolution or “focus” (**Figures 8 & 9**). It is anticipated that processing of the raw and focused microwave images will allow re-construction of the form of subsurface objects in a 3D rendering [7].

The holographic radar system is a portable device weighs less than 2 kg that can be carried in a briefcase for on-board inspection. It emits < 10 mW microwave that is safe for human. In practice, in addition to the plan-view footprint of subsurface objects, it may be important to measure their depth as well. This is an unsolved problem that JPL’s advanced pattern recognition and 3D imaging technology can play an important role[4].

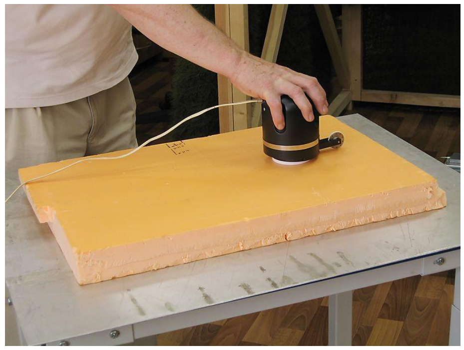


Figure 6: Hand-held Scanning Device.

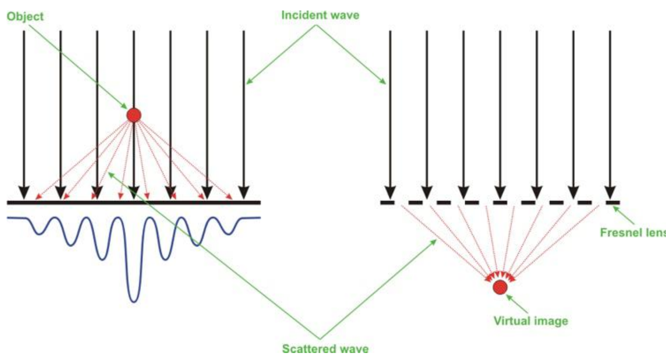


Figure 7: Recording and Reconstruction of microwave hologram.

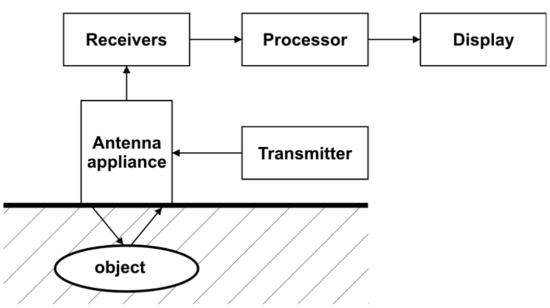


Figure 8: Block Diagram of RASCAN.

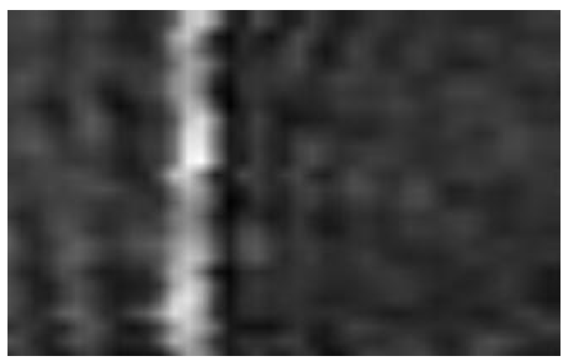
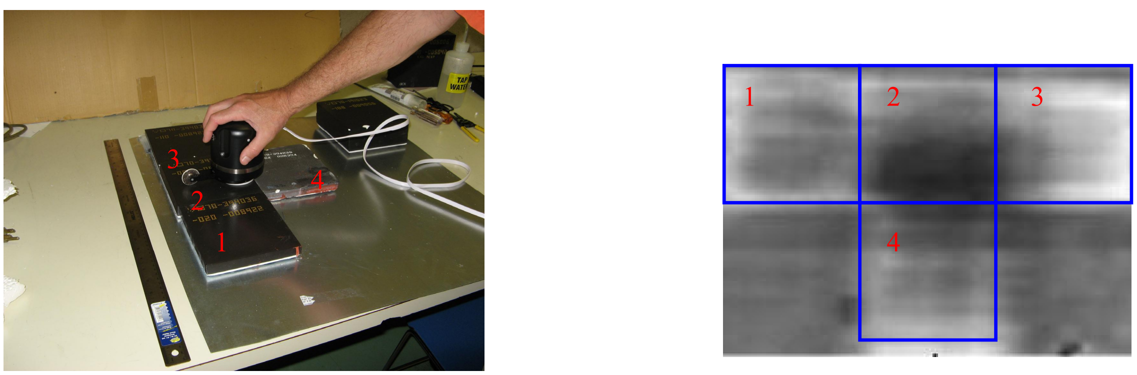


Figure 9: Sample images of defects.

3. EXPERIMENTAL TESTING

Initial experiments using Space Shuttle Thermal Protection tiles have shown that the RASCAN holographic radar can detect small voids and spots of moisture within the tile or foam material, and between the tile/foam and underlying substrate. As shown in **Figure 10**, four tiles, each 6 x 6 x 1 inch in size, were bonded in a T-shape on an Aluminum substrate. The bonding agent is a Permatex Ultra Black RTV Silicone Gasket Maker, a high temperature RTV silicon rubber adhesive sealant. The Aluminum plate was cleaned and dried before use. A thin layer of RTV was applied to the Aluminum plate. **Tile 1** was bonded with a layer of contamination (hand lotion) on the Aluminum plate before applying the RTV. **Tile 2** was bonded properly. **Tile 3** was bonded on the left half only. A stack of 4 pieces of regular white paper was placed between the RTV and the Aluminum plate to create an approximately 1 mm void on the right half of **Tile 3**. **Tile 4** was bonded with only a small spot of RTV in the upper center of the tile. The tile bonding was left to dry for 24 hours before experiment. **Figure 10**(a) shows the hand-scanning of the image. The RASCAN device was placed on top of the tiles. The scanning field must be flat so that the echo signal has a uniform bias. The RASCAN is handheld and moves horizontally in uniform speed. The distance between adjacent scanning lines is 1 cm, thus the resolution is approximately 1 cm. RASCAN manual scan of a 12 x 18 inch area took ~ 5 minutes. An automated scanning mode could be faster. The RASCAN combines the scanning signal and generates 10 grayscale images, a combination of 5 frequencies and two polarizations. We pick the image with best contrast, then post-process the image with smoothing and contrast enhancement. The resultant image is shown in **Figure 10(b)**. The very dark areas represent good bonding, while the lighter areas represent inferior bonding. We can see the area in **Tile 2** is the darkest, representing the proper bonding; the right half of **Tile 3** gives a strong reflection, revealing the loose bonding area; the area in **Tile 1** is a little lighter than **Tile 2**, which may be caused by the hand lotion layer between the RTV and the substrate; and the darker area in **Tile 4** also shows the effect of improper bonding. The edges of the tiles are slightly lighter, which may be caused by the voids in the edges and the reflection of signal by the boundary.



(a) **(b)**

Figure 10: ***(a)*** *Process of Scanning sample shuttle tiles:* ***Tile 1*** *was bonded with a layer of contamination (hand lotion) on the aluminum;* ***Tile 2*** *was bonded properly;* ***Tile 3*** *was bonded on the left half only;* ***Tile 4*** *was bonded with only a spot of RTV.* ***(b)*** *RASCAN image for the sample tiles: darker areas represent proper bonding, and the lighter area shows subnominal bonding (lateral resolution ~ 1 cm).*

In **Figure 11**, a single tile of 6 x 6 x 2 inches in size was evaluated with two bare areas of RTV. In the lower left bare area, we put several drops of water; the upper right is simply an air pocket. The image with two white spots shows these two. The wet holiday is large and brighter, possibly the water was smeared to neighboring area; the air pocket is smaller and more subtle, but still clearly visible in the radar image.

(a) **(b)** **(c)**

Figure 11: ***(a)*** *A thin layer of RTV was applied to the Aluminum plate. Two spots were left intentionally without RTV to create subnominal bonding: upper left part (1) has an air pocket; the lower right part (2) has water drops between the tile and the substrate;* ***(b)*** *A 6 x 6 x 2 inch tile was bonded on the place;* ***(c)*** *A RASCAN image of tile shows the subnominal bond (light part in upper left) and subnominal bond filled with water droplets (lighter part in lower right).*

4. DISCUSSION

The initial experiments have shown the holographic radar can potentially detect subnominal bonding, small voids, and moisture layers between the Space Shuttle Thermal Protection Tiles and the Aluminum substrate. The current experimental setup is still rough and qualitative. There are still noise and undefined reflections that need extensive testing and post-processing. We need to further study the dynamics of the detected signal, perform quantified analysis of the return signal related to the dielectric changes and the depth. JPL's intelligent neural network processing and 3D based image analysis algorithms can be used to post-process the images to yield more accurate measurement. The system can be designed for in-flight and ground-based non-destructive testing of large structures spacecraft. Now, new radar with higher resolution capacity is under development in Bauman Moscow State Technical University. The radar operates in frequency range of 5.8-6.8 GHz. We propose further research and development of innovative exploration vehicle structural health monitoring systems that provide real time in-situ diagnostics and evaluation of structural integrity.

5. ACKNOWLEDGEMENTS

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