HIGH RESOLUTION MILLIMETER WAVE DETECTION OF VERTICAL CRACKS IN THE SPACE SHUTTLE EXTERNAL TANK SPRAY-ON-FOAM INSULATION (SOFI)

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ABSTRACT. Space Shuttle Columbia's catastrophic failure, the separation of a piece of spray-on-foam insulation (SOFI) from the external tank (ET) in the Space Shuttle Discovery's flight in 2005 and crack detected in its ET foam prior to its successful launch in 2006 emphasize the need for effective nondestructive methods for inspecting the shuttle ET SOFI. Millimeter wave nondestructive testing methods have been considered as potential and effective inspection tools for evaluating the integrity of the SOFI. This paper presents recent results of an investigation for the purpose of detecting vertical cracks in SOFI panels using a focused millimeter wave (150 GHz) reflectometer. The presented images of the SOFI panels show the capability of this reflectometer for detecting tight vertical cracks (also as a function of crack opening dimension) in exposed SOFI panels and while covered by a piece of SOFI ramp simulating a more realistic and challenging situation.

Keywords: SOFI, nondestructive testing and evaluation, millimeter wave, space shuttle, crack.
PACS: 81.70.Ex, 07.57.-c

INTRODUCTION

Space Shuttle Columbia's catastrophic failure has been attributed to a piece of spray-on-foam insulation (SOFI) that was dislodged from the external tank (ET) and struck the leading edge of the left wing [1]. A piece of SOFI was also dislodged in the Space Shuttle Discovery's flight in 2005, and in 2006 a crack was detected in its ET foam prior to its successful launch. Millimeter wave nondestructive testing methods have been considered as potential and effective inspection tools for evaluating the integrity of the SOFI. Millimeter waves are electromagnetic waves with a wavelength between 1 and 10 millimeters and corresponding frequency of 30 GHz to 300 GHz [2]. SOFI is in the family of low loss and low permittivity dielectric materials and hence millimeter wave signals readily penetrate through it and can effectively interact with its internal structure including any anomalies such as voids, disbonds, delaminations, etc. that may exist in it [3]. To date, millimeter wave nondestructive testing (NDT) methods, using real (with focusing lens antennas) and synthetic focusing techniques including holography, have been extensively investigated for inspection of various SOFI panels representing realistic portions of the external tank [4-9]. These panels had embedded anomalies (i.e., voids, disbonds and delaminations) in them and some investigations involved blind panels with natural defects (i.e. voids, etc.) in them as a result of the manufacturing process. Real focused millimeter wave reflectometer systems that have been used at V-band (50-57 GHz), W-band (75-110 GHz) and D-band (110-170) incorporated lens antennas so that the radiating beam could be focused at a small footprint. The systems operating at 100 GHz and 150 GHz have been very successful in detecting the various anomalies mentioned above. However, the 150 GHz reflectometer system provided for a footprint of approximately 2 mm in diameter which resulted in higher spatial resolution. In addition, given the nature of the foam it is expected that at frequencies much above 150 GHz the signal experiences significant scattering within the foam (i.e., foam air pockets size approaching a significant portion of the incident signal wavelength) and therefore limiting signal penetration into the SOFI. At 150 GHz, the results of these investigations have shown the ability to penetrate twice (taking into account transmitted and reflected signals) through foam panels as thick as 23 cm (9 inches).

This paper presents the results of a specific investigation in which a cracked SOFI section, used to simulate a vertical crack with varying width (opening) while exposed and when hidden under a SOFI ramp, was inspected with the 150 GHz real focused reflectometer system.

MILLIMETER WAVE REFLECTOMETER

The general schematic of a typical reflectometer is shown in Figure 1. The oscillator generates the desired millimeter wave signal at a preset frequency (i.e., 150 GHz). A portion of the signal may be used as reference while the major portion of it is transmitted (through the divider) via a lens antenna. The reflected signal is then picked up by the same lens antenna and is compared with the reference signal. Depending on the type of information sought, a signal proportional to the magnitude and/or phase of the reflected signal is then obtained through the comparator. This signal is then properly conditioned (i.e., amplified, etc.) and is recorded. The recording of the signal is synchronized with the motion of a two dimensional scanner to which the reflectometer or the panel under investigation is attached. The oscillator requires a low voltage DC input while the system output is also a DC voltage making the entire system a simple and versatile one. This results in producing a raster scan of the panel. This system is small, compact, simple to use, portable, adaptable to existing scanning platforms, does not require modification of the existing testing environments, and is only a few tens of thousands of dollars as opposed to more expensive systems that may cost several hundreds of thousands or more. In this investigation the reflectometer operated at a frequency of 150 GHz and the lens antenna provided a footprint of ~2 mm at a focal distance of ~30 cm (or 12"). It is important to note that such lens antennas have a certain depth of focus associated with them. Consequently, to detect an anomaly the lens focal distance need not exactly coincide with the location of the anomaly in the SOFI for the anomaly to be detected. Anomalies located in the depth of focus will be detected as well but not as sharply as those exactly at the focal distance. This is a tremendous advantage of this particular technique since anomalies within the depth of focus are detected without the need to readjust the lens focal distance to "see" through a good portion of the SOFI depth. Moreover, since this is a continuous wave (CW) method (i.e., the signal is not pulsed) there is no need for time gating of the reflected signal to correspond to a particular depth within the SOFI. This method relies on the property and geometry changes between the SOFI host and any anomaly that may exist in it. There are other advantages in using these techniques and they are listed in detail in references [3-7]. A picture of the reflectometer system inspecting a thick SOFI ramp panel (~9" at its thickest part) is shown in Figure 2.

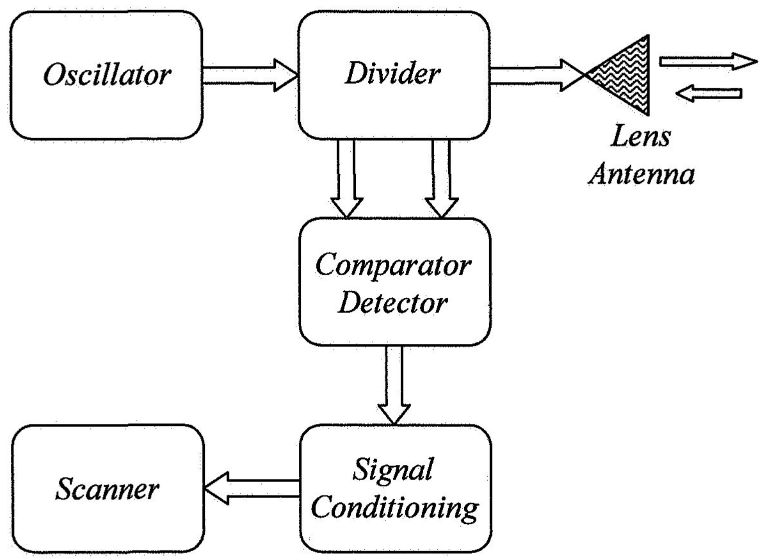


Figure 1: General schematic of a millimeter wave reflectometer.

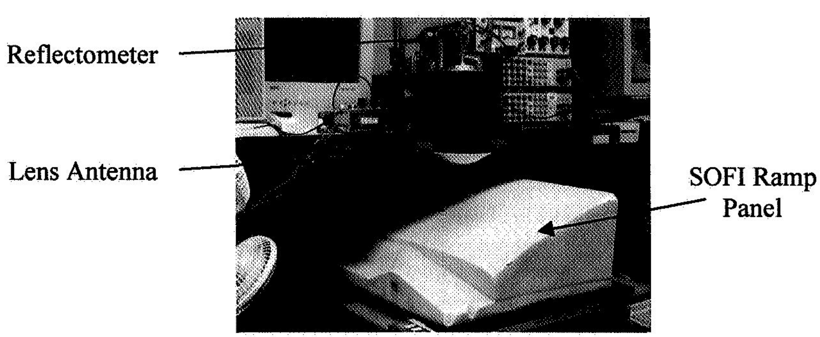
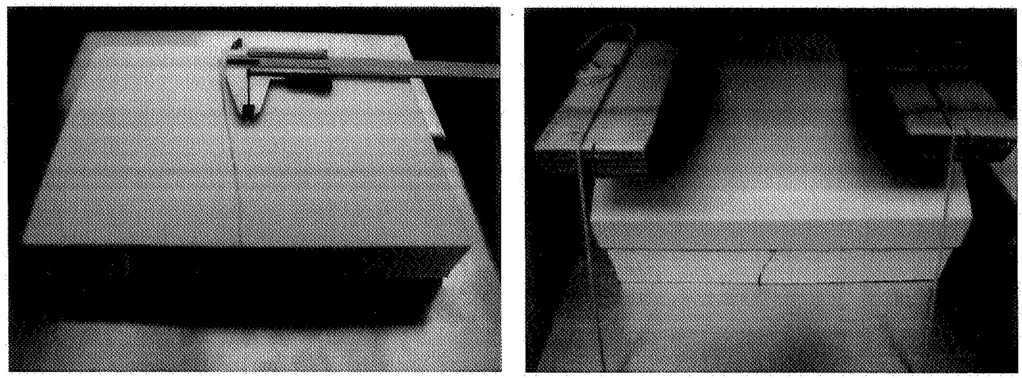


Figure 2: Picture of the reflectometer and the lens inspecting a SOFI ramp panel.



(a) (b)

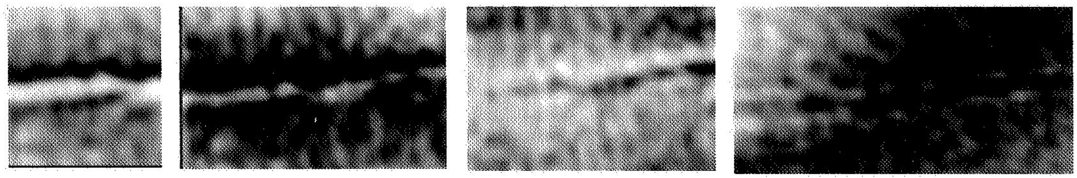
Figure 3: Vertical cracked SOFI sample a) exposed and b) under a piece of SOFI ramp.

SAMPLES DESCRIPTION

One of the issues that was raised recently had to do with whether a vertical crack in a SOFI block may be detected. Additionally, the crack opening may be exposed at the SOFI surface or may be hidden by another piece of SOFI (e.g., round of spray) that may have the shape of a ramp (i.e., varying thickness of SOFI over the crack). To this end three SOFI blocks were provided that could simulate these situations. Figure 3a shows the picture of two of these blocks with thickness of 38 mm that were broken out of one piece of 152 mm by 229 mm so that once put together they generated a vertical crack whose width was varied from about 0 mm ("*kissing*" vertical crack) to about 2 mm in this investigation. Vertical crack with a width just over 1 mm between the two blocks backed by 6-mm aluminum substrate can be seen in Figure 3a. Figure 3b shows the same two blocks placed under a 152 mm by 229 mm SOFI block made into the shape of a ramp, producing SOFI thickness from 25 mm to 70 mm over the vertical crack region. Several experiments were conducted in which many different scenarios were considered including *i*) detecting the vertical crack while the two pieces generating it were pushed firmly into one another producing a kissing vertical crack and *ii*) a crack whose width varied along its length.

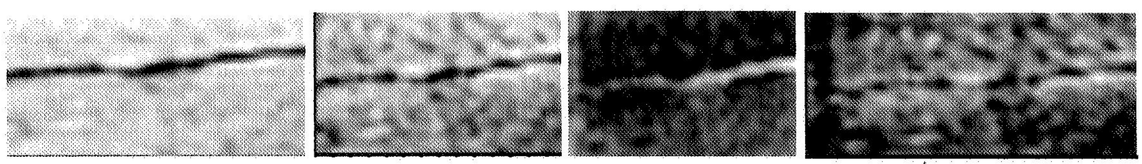
RESULTS

Figure 4 shows the images of the vertical crack for the exposed case (Figure 3a) with varying crack opening/width dimensions and when the lens was focused at the top surface of the SOFI sample. The two pieces of SOFI were placed next to one another and the resulting crack opening was varied from ~1.5 mm to when the two pieces were tightly pressing one another simulating a kissing or tight vertical crack. Figure 5 shows the results when the lens was focused at the aluminum substrate. The results clearly show the capability of this millimeter wave reflectometer to detect narrow vertical cracks. It is also important to note that the cracks were clearly detected for when the lens was focused at the top surface and the substrate of cracked SOFI sample under test. Another important observation is that the tight/kissing crack that was produced by tightly pressing the two pieces of SOFI was detected as well. This is a very significant issue indicating the potential capabilities of this 150 GHz reflectometer for detecting and imaging tight vertical cracks that may not be easily visible. Figure 6 shows the results for the case when the cracked SOFI sample was placed under a section of a SOFI ramp and the lens was focused at the substrate. The results show that the two cracks (~1.5 mm and ~1 mm wide) were detected once again. The most important result is that the 150 GHz reflectometer is capable for detecting hidden vertical cracks (cracks in depth of the SOFI under its non-cracked part with different thickness) because such cracks are the most critical in practice.



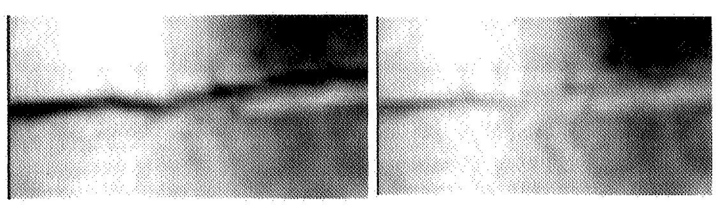
(a) (b) (c) (d)

Figure 4: Vertical crack images for exposed SOFI sample and when the lens was focused at the top surface of the SOFI sample for varying crack opening dimensions, a) ~1.5 mm, b) ~1 mm, c) ~0.5-1.5 mm and d) kissing (tight) crack.



(a) (b) (c) (d)

Figure 5: Vertical crack images for exposed SOFI sample and when the lens was focused at substrate for varying crack opening dimensions, a) ~1.5 mm, b) ~1 mm, c) ~0.5-1.5 mm and d) kissing (tight) crack.



(a) (b)

Figure 6: Vertical crack images for SOFI sample under the ramp section and when the lens was focused at substrate for varying crack opening dimensions, a) ~1.5 mm and b) ~1 mm.

SUMMARY

Millimeter wave imaging systems using real focused antennas such as lenses and synthetic aperture antennas have shown great potential for inspection the space shuttle SOFI for a wide range and dimensions of anomalies such as voids, disbonds. This investigation focused on detecting relatively tight vertical cracks in SOFI. This type of anomaly is difficult to detect since the crack plane is parallel to the propagation direction of the incident signal. However, the results of imaging several intentionally produced vertical cracks with varying widths when exposed and under a SOFI ramp and when the lens was focused at the surface of the sample or at its substrate are promising.

ACKNOWLEDGEMENT

This work has been supported by a cooperative agreement from NASA Marshall Space Flight Center (MSFC), Huntsville, AL.

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