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COMPARISON OF FOCUSED AND NEAR-FIELD IMAGING OF SPRAY ON FOAM INSULATION (SOFI) AT MILLIMETER WAVE FREQUENCIES

Sergey Kharkovsky[1], Reza Zoughi[1] and Frank L. Hepburn[2]

[1]Applied Microwave Nondestructive Testing Laboratory (*amntl*)
Department of Electrical and Computer Engineering
University of Missouri-Rolla, Rolla, MO 65409
Tel: (573) 341 4728, Fax: (573) 341 4352, E-mail: zoughir@umr.edu

[2]Marshall Space Flight Center
Huntsville, AL 35812
E-mail: Frank.L.Hepburn@nasa.gov

Abstract. Millimeter wave imaging techniques can provide high spatial-resolution images of various composites. Lens antennas may be incorporated into the imaging system to provide a small incident beam footprint. Another approach may involve the use of horn antennas, which if operating in their near-fields, images with reasonably high spatial-resolutions may also be obtained. This paper gives a comparison between such near-field and focused far-field imaging of the Space Shuttle Spray on Foam Insulation (SOFI) used in its external fuel tank at millimeter wave frequencies. Small horn antennas and lens antennas with relatively long depth of focus were used in this investigation.

Keywords: near-field, horn, lens, millimeter waves, imaging, SOFI

1 INTRODUCTION

The Space Shuttle Columbia's catastrophic accident has now been determined to be due to a piece of Spray on Foam Insulation (SOFI) that broke off from the external tank and damaged the leading edge of the orbiter's left wing [1]. Ever since that accident there has been a concentrated effort in determining and developing high-resolution imaging systems capable of inspecting the SOFI over complex regions of the external tank [2]. One such method that has received considerable attention is millimeter wave imaging using real aperture antennas as well as synthetic aperture and holographical methods [3-7]. At these frequencies, the signal propagates inside the foam without much attenuation so that thin and thick foam can be interrogated and there is still a reasonable and detectable distinction between the dielectric properties of the foam and discontinuities, rendering the latter detectable (that is, there is sufficient scattered signal). Moreover, at these frequencies, probe dimensions (i.e., an open-ended waveguide or a small horn antenna) are relatively small and, when used with optimal reflectometers (designed for imaging purpose), they can produce images with relatively high spatial-resolution [8]. In addition, both lens and horn antennas have been incorporated into these reflectometers, each having its own attributes. Lens antennas can be designed to suit a particular application and fulfill a certain set of measurement requirements such as focal distance, depth of focus and the focusing footprint size. Horn antennas can be small and the size of system with such small horn antenna can be significantly reduced. However, a small horn antenna produces a footprint that becomes larger as a function of increasing distance from the horn, and consequently spreads the incident signal over a larger area [9]. This may cause degradation in spatial resolution and also reduce the level of signal reaching into thick samples. Therefore, comparison of the focused and near-field methods is required for the purpose of detection and evaluation of defects in the SOFI. In this paper a comparison between these two distinct methods is provided using examples of images of SOFI samples produced with small horn antennas and lens antennas with relatively long depth of focus.

2 SOFI SAMPLES AND APPROACHES

Two SOFI samples were used in this investigation. One of the samples was a SOFI slab with five flat-bottom holes on top of aluminum substrate. This sample was from the set of SOFI samples prepared for investigation into evaluating the capabilities of the millimeter wave focused imaging techniques for detecting localized anomalies (i.e., voids) of different sizes and at different depths within the SOFI [3]. Figure 1 shows the picture of the SOFI slab (550 × 240 mm wide and 70 mm thick) in which five cylindrical voids with a diameter of 6 mm and with heights of very close to 25, 18, 12, 6, and 3 mm were milled. The spacing between the centers of any two voids was about 95 mm. The slab shown in Figure 1 was turned over and put on top of an aluminum substrate prior to imaging the holes. In this way, localization of the flat-bottom holes at the substrate was accommodated.

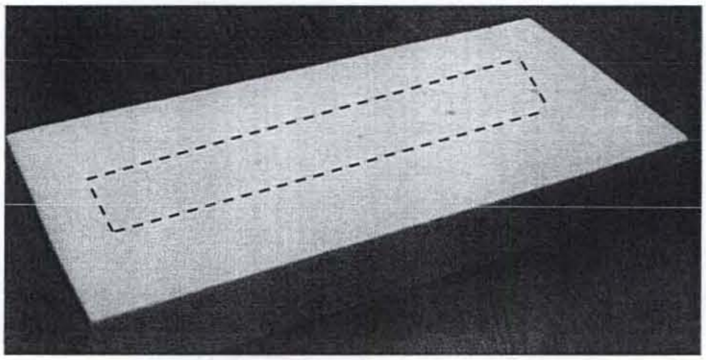
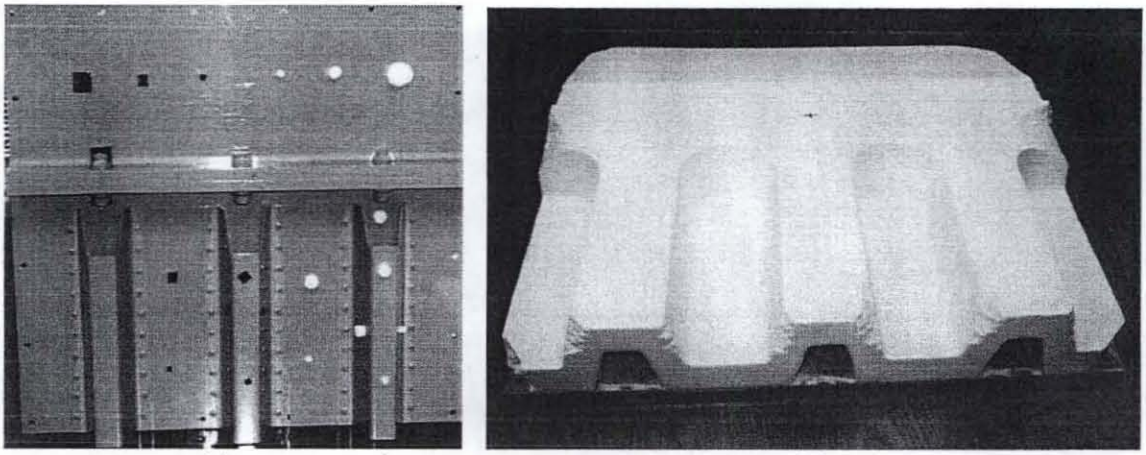


Figure 1: Picture of the SOFI slab with 6-mm diameter voids of different heights (area of the holes location is marked by dash lines).

Other sample was a SOFI panel designed to resemble the intertank flange portion of the external fuel tank and consisted of three stringers, a flange and three bolts through the flange centered in front of the stringer openings [4]. Figure 2 shows the picture of this SOFI panel before and after the application of SOFI. To represent localized flaws in the SOFI, rubber inserts (black squares) and SOFI void inserts (white circles) were placed at several critical regions of this panel, as shown in Figure 2a.



(a) (b)

Figure 2: The SOFI panel picture: a) before and b) after SOFI application.

In this investigation, several laboratory-designed millimeter wave continuous wave (CW) reflectometers were used for producing images of these samples at different frequencies from 33 - 150 GHz (Ka-band – D-band). In conjunction with these reflectometers, different small horn antennas and focused lens antennas were used. For instance, the W-band small horn antenna had aperture dimensions of 10 by 14 mm with a far-field operating distance of approximately 197 mm corresponding to a footprint diameter of approximately 50 mm at this distance [9]. Focusing lens antennas can produce much smaller footprints (e.g., narrow beamwidths) at their designed focal length (i.e., far-field). The footprint associated with W-band lens antenna used in this investigation was 12 mm at the focal length of 254 mm at the operating frequency of 100 GHz. 2D scans/images of the samples were produced at different frequencies and standoff distances (e.g., the distance between the horn or lens antenna and the surface of a sample). A DC voltage, proportional to changes of the power of the reflected signal from the sample, was then measured and recorded in a matrix corresponding to the scanning area. Subsequently, the measured voltages in this matrix were normalized (with respect to the highest voltage value), and a grayscale image of the panel was produced.

3 RESULTS

Figures 3a – b show the images of the SOFI slab at frequencies of 70 GHz (V-band), and 100 GHz (W-band) using the near-field approach with a small horn antenna, whereas Figure 3c shows the image of this sample at 100 GHz using the lens antenna with the 12-mm-diameter footprint. Dimensions of scanned area for these images were 420 mm by 70 mm. The images obtained with the horn (Figure 3a and b) show the holes (voids), which are manifested by rings indications, while the indications of the holes in the images obtained with the lens antenna are manifested by circles. As expected, the stronger indication corresponds to the deeper hole. From Figure 3, it is visible that four of the holes (voids) are clearly detected.

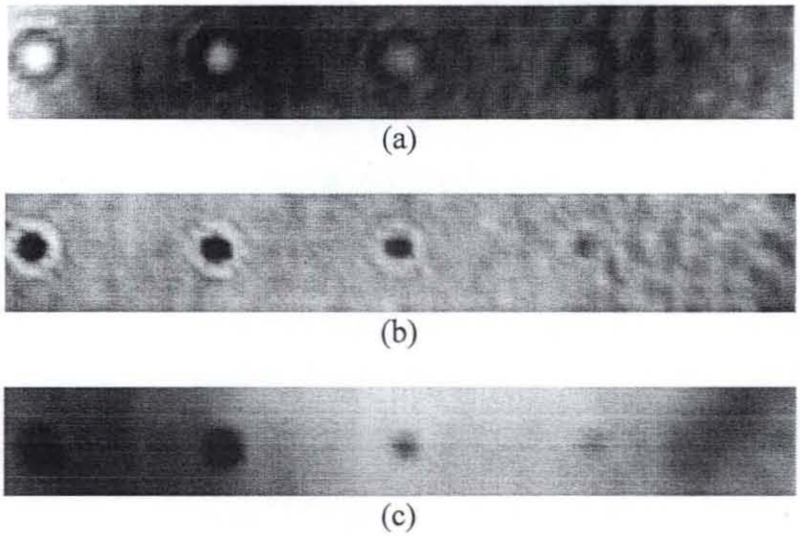
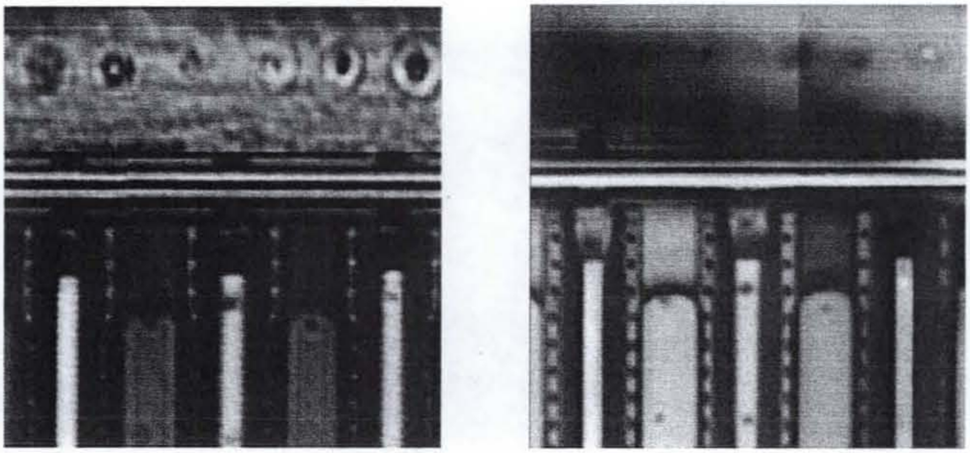


Figure 3: Images of the SOFI slab with holes backed by metal plate obtained with (a) the small horn antenna at 70 GHz, (b) the small horn antenna at 100 GHz and (c) the lens antenna at 100 GHz.

The 3-mm height hole is not detected using the horn antenna at 70 GHz, while it was detected, at least to some degree, using the horn and lens antenna at 100 GHz. Figure 4 shows the V-band images of the SOFI panel using a small horn antenna and a lens antenna with a 12-mm diameter footprint and a depth of focus of approximately 100 mm. The panel was located in the near-field of the horn antenna and in the depth of focus region of the lens antenna (the lens was focused at the substrate). In both images the primary features of the panel as well as most of the embedded flaws are seen. However, the image with the lens is much sharper and the geometrical features of the panel are much better revealed including those of the flaws. The result shown in Figure 4 also indicate that the shape and diameter of the indications obtained with the lens antenna is more closely correspond to the actual shape and diameter of the holes than the indications obtained with the horn antenna. This is primarily due to the size of the footprint in each case (i.e., smaller footprint in Figure 4b than in Figure 4a). The most important feature of these images is that both images provide through thickness information. In the case of the horn antenna this is due to intrinsic feature associated with the near-field of horn antennas. In the case of used lens antenna this is due to its relatively long depth of focus.



(a) (b)

Figure 4: Image of the SOFI panel (a) at 70 GHz using a small horn antenna and (b) at 73 GHz using a lens antenna focused at the substrate.

4 SUMMARY

Millimeter wave imaging systems using horn and lens antennas are viable systems for inspecting and imaging SOFI samples. Lens antennas are capable of focusing the incident beam and produce high spatial-resolution images. Focusing of the beam also translates to higher gains associated with lens antennas and therefore thin and thick SOFI may be imaged with reflectometers using lenses. The horn produces a footprint that becomes larger as a function of increasing distance from the horn, and consequently spreads the incident signal over a larger area. This causes degradation in spatial-resolution in particular when imaging relatively thick samples. However, once a system with a horn antenna is optimized, its utility becomes very attractive from a practical point of view. For relatively thin SOFI small horn antennas may be used for generating high quality images of the samples when located in the near-field region of a horn. The size and cost of the system with a small horn antenna can be significantly less than the size and cost of the system with a lens antenna.

One of the most important features of imaging using the continuous wave reflectometer with a *near-field* horn antenna and a lens antenna with relatively *long depth of focus* is that once an image is produced it provides through thickness information. This is an advantage of using these techniques because multiple flaws located at different depths within the SOFI can be simultaneously detected in one scan/image (i.e., no need to change lens distance to a sample to detect flaws at different depths). If necessary, one may subsequently use various approaches to hone in on a particular depth to obtain a clearer image from that depth. This may be accomplished using the high-resolution focused lens antennas [3-5] or by using signal processing techniques such as synthetic aperture focusing and holography [6-7].

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