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FLAW INVESTIGATION IN A MULTI-LAYERED, MULTI-MATERIAL COMPOSITE: USING AIR-COUPLLED ULTRASONIC RESONANCE IMAGING

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ABSTRACT. Ceramic tiles are the main ingredient of a multi-material, multi-layered composite being considered for the modernization of tank armors. The high stiffness, low attenuation, and precise dimensions of these uniform tiles make them remarkable resonators when driven to vibrate. Defects in the tile, during manufacture or after usage, are expected to change the resonance frequencies and resonance images of the tile. The comparison of the resonance frequencies and resonance images of a pristine tile/lay-up to a defective tile/lay-up will thus be a quantitative damage metric. By examining the vibrational behavior of these tiles and the composite lay-up with Finite Element Modeling and analytical plate vibration equations, the development of a new Nondestructive Evaluation technique is possible. This study examines the development of the Air-Coupled Ultrasonic Resonance Imaging technique as applied to a hexagonal ceramic tile and a multi-material, multi-layered composite.

Keywords: Vibrational Resonance, Air-coupled Ultrasonics, Resonance Imaging
PACS: 43.20.Ks, 43.35.Zc

INTRODUCTION

Ultrasonic testing has long been used in Nondestructive Evaluation (NDE) for flaw detection and characterization. Most of the ultrasonic testing techniques have used water or some other liquid couplant due to their relatively low attenuation. This allows for a high amount of energy to be transferred into a sample. The advent of composites and other couplant sensitive materials, as well as their subsequent integration into many industries (such as the aerospace industry) necessitated the development and use of non-contact NDE methods.

Acoustic non-contact methods have historically been very difficult to use due to the enormous loss of energy at the air-solid interface and the inefficient transfer of acoustic energy through air. Over the last two decades, more efficient transducers were developed for the generation and reception of air-borne ultrasound, thus enabling the non-contact, non-contaminating inspection of composite laminates and honeycomb structures widely used in the aerospace industry. [4]

Since its inception, Air-coupled Ultrasonic Testing (ACUT) has been treated as a low frequency version of water-coupled ultrasonics, and its development and uses are described in the references [1-7]. Because of this treatment almost no techniques have been developed that utilize the strengths of ACUT. Trying to use the techniques developed for Water-Coupled inspection with ACUT has provided less than spectacular results. This chapter explores a new testing method for ACUT that utilizes resonance imaging.
PROBLEM STATEMENT

A new composite material is being considered for the modernization of tank armors. It is composed of several layers of different materials (Fig. 1) and will thus be referred to as a multi-layer, multi-material composite. Each layer is composed of a different material from its neighboring layers, and each material has very different mechanical and acoustical properties. The objective of this research is to detect flaws in the SiC tiles, or at any of the interfaces. Any flaws will affect the resonance image of the material and thus will be detectable. This technique is called Air-Coupled Ultrasonic Resonance Imaging (ACURI).

FLAW DETECTION USING ACURI METHOD

The question for this new flaw detection method is whether or not flaws can be detected and characterized in a multi-layer, multi-material composite lay-up using ACURI. The three samples used to explore this question are referred to as Panel A, Panel B, and Panel C and have the properties listed in Table 1.

All of the tests performed on the three panels are ACUT c-scans. The transducers used were Quality Material Inspection (QMI) spherically focused probes with center frequencies of ~120 kHz and ~225 kHz (bandwidths of ~25%) which were held ~2 in from the sample. The signal was impinged on the graphite side of the lay-up and was received on the S2 glass side of the lay-up.

The scans of Panel A, for both frequencies mentioned above, are shown in Fig. 2. The SiC tile can be easily distinguished from the alumina tiles due to a difference in the resonance patterns of the tiles. In the 120 kHz image, the SiC tile exhibits a spoke-like pattern where the alumina tiles show a different pattern. At 225 kHz image, both the alumina and the SiC have similar resonance patterns, however, the amplitude of the resonance patterns is different, and the SiC tile can still be easily distinguished.

Since there are no known defects over the SiC tile in this panel (Panel A), these resonance images will be used as a basis for comparison for the panels with defects. The resonance patterns have been outlined in Fig. 3 to make comparisons easier. The 225 kHz pattern is too intricate to use the entire pattern and since the defects are primarily over the center of the tiles only the inner part of the pattern will be used.

TABLE 1. Depiction of material samples and embedded defects.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Size</th>
<th>Material of tiles</th>
<th>Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A</td>
<td>14”x15”x1.5”</td>
<td>1 SiC rest alumina</td>
<td>No known defects</td>
</tr>
<tr>
<td>Panel B</td>
<td>16”x18”x1.5”</td>
<td>6 SiC tiles rest alumina</td>
<td>6 simulated disbonds</td>
</tr>
<tr>
<td>Panel C</td>
<td>21”x25:x1.5”</td>
<td>18 SiC and 10 alumina</td>
<td>30 embedded defects, 12 inclusions, 18 disbonds</td>
</tr>
</tbody>
</table>

FIGURE 1. Depiction of the materials and layers of the multi-layer, multi-material composite.
The approximate size and location of both the alumina and SiC tiles of Panel B are shown in Fig. 4. The approximate size, shape, and locations of the six engineered disbonds (created to simulate the effect of the inclusion of air during the manufacture of the lay-up) are also indicated. The disbonds are square, centered over the center of the SiC tiles, and come in the sizes of 0.5 in, 1.5 in, and 2.5 in. The shape is for the ease of fabrication and the size to test the detection limits of this investigation. The top row, labeled as row 1, has the disbonds between the rubber and S2 glass layers while the bottom row, labeled as row 2, has the disbonds between the graphite and rubber layers.

Fig. 5 shows the scan results for Panel B as well as the undamaged SiC tile from Panel A at 120 kHz. In Fig. 5-b the approximate size, shape, and location of the disbonds are outlined. Fig. 5-b shows that the 1.5 in and 2.5 in disbonds are clearly visible as dark cloudy areas in both the top and bottom rows. Furthermore, the 0.5 in disbonds in the top row can be detected via a disruption of the resonance pattern when compared to the pattern of the tile with no known defect (Fig. 5-a) due to a large change in the amplitude and clarity of the resonance image. A closer inspection of the image in Fig 5-b shows a significant difference between the top and bottom rows. This means the difference in the disbond locations can be distinguished with through transmission due to these resonance patterns.

In Fig. 5-c the resonance patterns have been highlighted for easier comparison. If the top row of images is visually compared to the bottom row, the differences in the resonances are apparent. The bottom 0.5 in defect pattern matches very closely with the pattern of the tile with no known defect (Fig. 5-a) while the top 0.5 in defect pattern has a significantly different amplitude and seems to have been disrupted by something. Comparison of the 1.5 in defect patterns shows that they are basically the same as the 0.5 in defect patterns, that they show the same relation, but with a very low amplitude region in the approximate location of the disbonds. The top 1.5 in defect pattern is fairly chaotic and even though some of the resonance pattern is detectable it has been disrupted by the disbond significantly more than the bottom
FIGURE 4. Layout of Panel B showing the approximate size and location of the ceramic tiles. The approximate size, shape, and locations of the 6 simulated disbonds are shown. The disbonds are located between different layers in the layup as indicated by the right part of the figure.

FIGURE 5. C-scan of Panel B at 120 kHz. (a) Resonance image of the bare SiC with 120 kHz resonance pattern outlined. (b) 120 kHz scan of full layup panel with six engineered disbonds outlined. (c) 120 kHz scan of full layup panel with six engineered disbonds and the resonance patterns outlined. The images are produced by taking the amplitude maximum of the received waveform over the entire time gate.

pattern. The top 2.5 in defect pattern is very chaotic and there is no detectable resonance pattern though the pattern is evident in the bottom row. The pattern in the bottom row matches the pattern of the tile with no known defect quite well (though much lower amplitude). There is also a secondary pattern (outlined in yellow-orange), though what causes this is unknown.

It is clear from these comparisons that 5 out of 6 of the disbonds are detectable with ACURI at a frequency 120 kHz and that there is a significant and noticeable difference between the resonance images of the disbonds located between the rubber and glass layers and the disbonds located between the graphite and the rubber layers.

Fig. 6 shows the same two panels shown in Fig. 5, but using a 225 kHz transducer instead of a 120 kHz transducer. Again the first image (Fig. 6-a) shows the resonance pattern of the tile in the lay-up with no known defects, the second image (Fig. 6-b) outlines the six engineered defects, and the third (Fig. 6-c) highlights some of the resonance patterns. A quick glance at the scan image shows that all 6 of the disbonds can be seen. Also evident is the difference between the top and bottom rows, namely that two of the three bottom disbonds have discernible resonance patterns while only one of the top disbonds has a discernible resonance pattern. Looking at the 0.5 in disbonds, the top and bottom patterns are very similar and match well with the no defect pattern, however, the high amplitude center, clearly visible
in the no defect pattern, is not present. This indicates that both of the 0.5 in disbonds are detectable. The resonance pattern is still detectable for the bottom 1.5 in discobnd, but not for any of the rest of the disbonds.

From these comparisons it is evident that 6 out of 6 of the disbonds are detectable with ACURi at a frequency of 225 kHz and that there is a significant and noticeable difference between the resonance images of the disbonds located between the rubber and glass layers and the disbonds located between the graphite and rubber layers. All six of the disbonds were easily detectable by comparing the defective resonance patterns with the non-defective patterns. Moreover, a difference in flaw location (which layers the flaw is between) can also be seen by comparing resonance patterns.

A possible explanation for the different disbond locations affecting the resonance patterns differently lies in the way in which the disbonds were engineered. Essentially there is a void for each disbond. Consider the vibrational displacement of the layers. The SiC tiles have the largest displacement (due to the vibration) of all of the layers. If the void/disbond is located between the second graphite layer and the rubber layer, the displacement of the graphite layer due to the SiC vibration may be larger than the thickness of the void/disbond and the displacement can be transferred to the subsequent layers. If the void/disbond is located between the rubber layer and the S2-glass layer, the displacement of the rubber layer due to the vibration of the SiC tile may be smaller than the thickness of the void/disbond and the displacement cannot be transferred to the S2-glass layer. This is because the rubber has a low modulus and high damping that will absorb a significant portion of the displacement of the graphite layer.

The approximate size and location of both the hexagonal alumina tiles and the hexagonal SiC tiles of Panel C are shown in Fig 7. The approximate size, shape, and locations of the 30 engineered defects are also indicated. The materials included in the lay-up (mold release and grease) and their locations are indicated in the figure. The inclusions are circular, centered over the center of the SiC tiles, and come in the sizes of 0.5 in and 1 in. The disbonds are circular with each group of three centered over the center of the SiC tile and are made by including two circular layers of kapton of different thicknesses. Including two layers of kapton will create a “kissing” disbond that will transmit the signal when in compression but not in tension. As indicated in the figure, the six columns have two different sizes of defects and the defects are located between different material layers. The defects in Panel C were created to simulate the effect of different types of possible inclusions during the manufacture of the lay-up and disbonds that may occur. Again the sizes are arbitrary and are merely to test the detection limits.
FIGURE 7. Layout of Panel C showing the approximate size and location of the ceramic tiles. The approximate size, shape, and locations of the 30 defects are shown. The defects are located between different layers in the layup as indicated by the right part of the figure.

Figure 8 shows the results from two resonance scans of Panel C, the first at 120 kHz and the second at 225 kHz. A comparison of all of the alumina tiles outlined in the figure shows a drastic difference in the amplitude and clarity of the resonance patterns, especially in the 225 kHz scan. Neither the scans of Panel A or Panel B show a similar issue. This indicates some deviation in the manufacture or handling with respect to Panels A and B. ACUT signals are sensitive to variations in the lay-up not caused by engineered defects, variations such as dry patches or delaminations. These variations can cloud or mask the actual engineered defects, which mean that the presence of both engineered and accidental defects could make flaw detection difficult with this technique. Even though any results from Panel C cannot be considered valid, a comparison of Panel A and Panel C yields some indications of flaw detection.

Figure 9 shows the scan results for Panel C as well as the undamaged SiC tile from Panel A for the frequency of 120 kHz. In Fig 9-b the approximate size, shape, and location of the defects are outlined. Although the scan does not have very defined or consistent resonance patterns on the SiC tiles, two SiC tiles show indications of defects. Fig 9-c highlights six dark, cloudy, circular shapes in the fourth and fifth tiles of the bottom row of SiC tiles. These six...
Figure 9 shows the C-scan results for Panel C as well as the undamaged SiC tile from Panel A for the frequency of 225 kHz. In Fig 10-b the approximate size, shape, and location of the defects are outlined. Again the scan shows signs of some sort of unknown problem. Fig 10-c highlights differences in the resonance patterns between Panel A, with no defect, and Panel C. It is easier to highlight the differences because of the complexity of the resonance pattern. The highlighted differences in the top two rows of SiC tiles correspond with the grease and mold release inclusions and eleven of the twelve are detected because the high amplitude center in the resonance pattern is absent. The high amplitude center is again absent in the first three resonance patterns of the bottom row of the SiC tiles. This indicates a flaw of some kind but does not indicate the three simulated disbonds. The resonance patterns in the fourth and fifth SiC tiles in the bottom row are completely disrupted with possible indications of the circular disbonds. The sixth resonance pattern in the bottom row also shows evidence of disruption in locations that correspond with the locations of the disbonds.
Although the scans of Panel C did not produce very clear images and any conclusions can only be treated as conjectures, there is good evidence that the flaws would have been detectable in a better constructed sample. Eleven of the twelve inclusions and six of the eighteen disbonds were detectable with some certainty.

DISCUSSION AND CONCLUSION

The multi-layer, multi-material composite armor considered in this study provides some difficulties for many traditional NDE techniques. The ceramic tiles at the center of this composite material have special properties that can and should be utilized when creating an optimized detection technique. These SiC tiles are remarkable resonators when driven to vibrate, and there are many distinct natural resonances with distinctive resonance patterns within the bandwidth of the transducers used. It has been shown that these resonance patterns can be used to detect and characterize flaws. All six of the engineered disbonds in Panel B were detectable along with information indicating between which two layers the disbonds were located. Even with the poor scan results from Panel C eleven of the twelve inclusions and six of the eighteen disbonds were detectable.

The ACURI technique developed in this study shows great promise for this material specifically and for several different types of materials in general. More work needs to be done by scanning samples containing different defects, using frequency scans (cw scans at specific frequencies), and using image processing to detect flaws.

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