Low frequency GFRP imaging with variable aperture TFM

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Abstract

Graphite or glass fiber reinforced polymer (GFRP) inspections are usually made with a zero-degree linear scan (L-scan) (1). Total focusing may not be applicable for some anisotropic materials, but in some cases, TFM may increase the ultrasound imaging quality. The imaging potential of 1D linear probes has been broadened by TFM by many aspects so there is an opportunity to apply the total focusing concepts to exotic composite assessment. The ultrasonic limitations associated with testing thicker sections of GFRP restrict inspections to lower frequency phased array probes. When a low frequency probe uses the L-Scan technique, the performance and sensitivity is negatively affected once compared to a typical phased array probe of a higher frequency due to the element size and pitch restrictions associated with low frequency probes. Therefore, new testing techniques should be found. The alternative imaging acquisition method presented here involves variable aperture receivers that improve the usual L-Scan characteristics. This study explicitly covers the differences over the L-scan type, the TFM image and its variable aperture TFM feature. In addition of the theory concepts, ultrasound metrics have been recorded on a real GFRP sample and using as reference reflector side drilled holes (SDH).

KEYWORDS: TFM; Phased Array; Ultrasound; Composite inspection; GFRP

1. Introduction

1.1 Challenge

Glass fibre reinforced polymer (GFRP) (2), as like most composites, presents a big challenge for ultrasound inspectors. Due to its anisotropic structure and/or to the high attenuation levels, ultrasound inspection is nearly impossible when using a conventional approach. Advanced phased array approaches as like TFM approach can overpass, in some cases and under some circumstances, the issues that have been mentioned above. The probe frequency will consequently limit the size of the smallest defect. The compromise is caused by a large grain anisotropic GFRP material structure. The probe
choice should allow the detection of anything above 1.75 mm (wavelength/4) and will not likely scatter on its fibre size less than 0.7 mm (wavelength/10). The advantage of this 0.5 MHz probe is the low attenuation response over thick composite material. Our material has a much larger attenuation coefficient than 100 dB/m for a 5 MHz probe which places the part far from the 1-10 dB/m amplitude drop for usual steel and aluminum properties (3). A few metrics are shown in the following table:

<table>
<thead>
<tr>
<th>X3A Probe</th>
<th>X6B Probe</th>
<th>Ratio Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 mm pitch</td>
<td>2 mm pitch</td>
<td>3.33x</td>
</tr>
<tr>
<td>38.4 mm active aperture</td>
<td>128 mm active aperture</td>
<td>Idem</td>
</tr>
<tr>
<td>5 MHz</td>
<td>0.5 MHz</td>
<td>10x</td>
</tr>
<tr>
<td>0.7 mm wavelength</td>
<td>7 mm wavelength</td>
<td>Idem</td>
</tr>
</tbody>
</table>

1.2 Linear scanning and TFM testing

It was possible to generate a TFM image designed for linear applications (4). The TFM scan uses the LL Propagation Mode calibrated at 3500 m/s for the compression wave mode. For the acquisition step, many different receiving aperture sizes have been tested. This SMC/TFM technique considerably increases the frame rate acquisition speed because it requires fewer elementary A-scans to process and less pulse and receives signals. By having similar and known advantages to DDF, this unique TFM acquisition should decrease all the constant focusing disadvantages of a zero-degree linear scan. It is worth noting that TFM LL legs may also contain higher refracted angle components than DDF. The default TFM ordinarily uses 100% of the Rx elements. In other words, this represents 64 sequences of one Tx element for all 64 (100%) Rx elements. The smaller captured matrix may contain a sparse matrix capture (SMC) parameter of 6%, 12%, 25%, 50% and 100%.

2. Methodology

2.1 Material

There are many types of GFRP. The sample used for this study is a blend of the composite and concrete technique. The following weight ratio has been described in the chemical content datasheet:
- Between 15 and 50% of polyester resin or vinyl ester
- Between 0 and 50% of crystalline silica sand and/or calcium carbonate (Chalk)
- Between 5 and 30% of fibreglass

GFRP sample properties were compared to an existing velocity study about GFRP. The sample used on this study has a density of 2.24 g/cm3 and a velocity of 3500 m/s at 0.5 MHz at 22 degrees Celsius. They confirmed the effect of higher velocity on low proportions of epoxy/resin glue. The current testing sample contains a very high quantity of fibreglass but also a high ratio of minerals. The sand and chalk densities are higher than fibreglass, which also explains the high density. The sound velocity is closer to the concrete property, which is about 3500 and 4000 m/s³.
Three side drilled holes (SDHs) have been made on the sample to allow more tests. All SDHs 1.9 mm in diameter. TCG points could then be recorded at 25%, 50% and 75% of their nominal thickness. These reflectors were also used to evaluate the beam width dimension, signal-to-noise ratio and attenuation.

2.2 Instrument and sound beam evaluation

A VEO3 32:128 instrument with Full Matric Capture (FMC) and TFM recording capabilities was used as the data acquisition system. The probe is an X6B-0.5M64E-2x10-SQX5. The couplant is water by direct contact inspection. This test required two measurements, the baseline noise amplitude in front of the reflector (SDH in this case) and the amplitude of the SDH. The ratio was expressed in dB by the following formula:

\[
SNR(dB) = 20 \times \log\left(\frac{\%\text{FSH Baseline Noise}}{\%\text{FSH Reflector}}\right)
\]

The beam width was equivalent to the active aperture, so the beam width ends at 6 dB lower than its centerline highest amplitude. The beam error was half the TFM resolution and half the pitch for the L-scan. (±0.25 mm and ±1 mm, respectively).

3. Results

3.1 SNR comparison

L-scan aperture and delays were fixed, and the SNR was compared among three different focusing depths. The minimum acceptable SNR was determined at 6 dB (i.e. a factor of two between a reflector and noise). When the reflectors were inside the focal range, only the 22 and 32-element aperture L-scans passed the SNR criterion.
There was, although, a major limitation when using high aperture focusing on fixed element delay sequences. Figure 2 is an example of the 32-element side view when the focusing was close to the SDH and when the focusing depth was 35 mm away from it. The SDH size was too large when the focus was offset by its location. In addition, the SNR failed as well.

### 3.2 L-Scan and TFM SRR performance

The number of active elements for both acquisition types made a difference for the receiving energy. This was also affecting both the SNR and the required scanning gain. The following graph displays the SNR performance regarding the number of elements used in the scan.

![Figure 3. SNR on TFM and L-Scan (higher is better).](image1)

It was also interesting to see the required scanning gain for the two techniques. The predicted gain behaviour was a higher scanning gain inspection for lower aperture size sequences. Together with the SNR, Figure 4 provides a comparative result over the amplitude sensitivity for the same reflector. It is possible compare the gain over different aperture sizes thanks to the normalized A-scan amplitude feature. Otherwise, the 16-element versus the 32-element scan would appear 6 dB better (twice the element, 2x more sensitive). The TFM requires about 12 more dB than the L-scan, but the 55 dB scanning gain is only at t/3 of the entire instrument gain range. The maximum acquisition gain is 80dB.

![Figure 4. Scanning gain compared to different aperture (lower is better).](image2)
3.3 SDH echo width comparison

The inspection must respect the SNR essential criteria, although its echo width result may also affect the sizing performance. The large, fixed aperture L-scan focusing was likely to cause a narrow beam despite its short focal range. The SDH echo spot is weak and wide, as confirmed in the situation in Figure 2 on the right. An unfocussed 32-element beam width gave the worst sizing among all the tests.

![Figure 5. Echo Width compared the Active Receiving Aperture (Lower is better).](image)

The TFM provided a constant and low beam width effect for all apertures and reflector positions. This was the most critical and compelling performance compared to traditional L-scans. Even the small Rx TFM aperture data shown consistent results. Please note that sample SDH was 1.9 mm in diameter, and the probe wavelength was 7 mm. This was a ratio of 27%, and the sensitivity response was acceptable. The 6 mm echo width was very close to the wavelength, but there was no relationship between the two. The wavelength dimension axis effect was perpendicular to the horizontal echo width.

3.4 TCG results

Timed-Corrected Gain (TCG) is useful when the material attenuation makes it difficult to size assessment over great distances. The amplitude dynamic echo was recorded along the index axis from 3 different depths. Figure 6 is an example of one dynamic echo along the active aperture (right half only). The BeamTool10 sensitivity result over a larger Region of interest (ROI) than the probe index length.

![Figure 6. Sensitivity Envelope along the Active Array Axis and its full 2D Coloured Map.](image)

As the ZOI can be larger than its probe equivalent L-scan index width, the amplitude dramatically drops outside the element's zero-degree area. When the SDH reflector reached down to 20 %, the first 17 mm depth TCG point could be set as far as 16 mm
away from the probe. The middle and deepest SDH reflector could only be calibrated at the end of the last element. According to the TCG point data, the 4 Rx element aperture TFM only requires an overall 1 dB more gain than a 16 Rx element TFM.

![Image](image.png)

*Figure 7. TCG Image Result and Its Red Dynamic Envelope on the Right*

It was possible to extract a 0.21 dB/mm amplitude drop along the 45 mm SDH constant depth line once the ZOI was outside the element index zone. The average TCG vertical line compensation has been estimated at 0.125 dB/mm. (125 dB/m or 3.175 dB/inch).

4. Results

This low-frequency inspection could never be solved entirely without the TFM capabilities. The L-scan could not pass based on low SNR results. Even the high aperture sequences reveal a short focal range, hence very short ZOI. The TFM and small aperture SMC is a good compromise that alleviates all L-scan issues. TFM is also interesting for larger ZOI inspection and higher lateral resolution. For practical TCG purposes, calibrating underneath the probe’s active area is easily performed and recommended. This imagery method additionally confirms its better beam width performance, providing better sizing accuracy. This recent imaging technique could be applied for most existing L-scan applications, such as corrosion mapping. This TFM recording process could even be applied on a wide 128-element PA probe using the existing instrument without the entire 128:128 pulse and receive power.

References