Evaluation of the imaging performance of a CFRP-adapted TFM algorithm

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Abstract

Structural composite components of several centimeters thickness are increasingly used in the energy industry. Consequently, the demand for more reliable and sensitive non-destructive testing techniques for such structures is also rising. In the case of ultrasonic testing, lower test frequencies are often used to temper prominent effects like scattering or absorption in thicker polymer matrix composites. This facilitates the inspection but also reduces the sensitivity to small reflectors. Novel array reconstruction algorithms such as the total focusing method (TFM) counteract this issue.

Recent studies of our group demonstrated that modifications of the TFM are necessary to reconstruct full matrix capture (FMC) acquired data for carbon fiber-reinforced polymers (CFRP). First, constructive superposition of reflector signals is achieved by considering the anisotropic sound velocity within the material. Second, the noticeably smaller divergence angle of a single-element transmission, compared to that in isotropic metals, should be taken into account. As a result, the signal-to-noise ratio (SNR) in the ultrasonic image and the detectability in the near-subsurface region (close to the transducer) is increased.

This paper describes the successful application of an adapted TFM algorithm to image small artificial defects in a 20 mm thick CFRP laminate. Of particular concern is the evaluation of its imaging performance to reconstruct side-drilled holes (1.0 mm and 3.0 mm in diameter) located at different depths. The SNR and the spatial resolution of the reconstructed images are evaluated and optimized. Ultrasonic imaging artifacts that occur in the TFM images are discussed. This contribution also addresses the challenge of inspecting thick and highly attenuative composites using the total focusing method. To this end, two similar arrangements of side-drilled holes for aluminum and CFRP were examined and their TFM results compared.

1. Introduction

According to current market forecasts, it is expected that the global demand for carbon fiber-reinforced polymers (CFRP) will continue to rise in the next few years (1, 2). The need of many industries for structural lightweight components is the main driver of this growth. It follows that, meaningful non-destructive testing techniques are becoming increasingly important for their inspection.

Ultrasonic testing (UT) is an essential method to reliably detect and characterize many significant defect types in fiber-reinforced polymers (3-5). Established ultrasonic
procedures exist, for example, to size delaminations (6, 7) or to quantify porosity contents (4, 8, 9). Composite laminates, however, pose a challenge to UT due to their inherent heterogeneity, high sound attenuation and elastic anisotropy. The latter, for example, results in significant angle-dependent sound wave velocities within the material. This is the main reason why for most well-established UT techniques longitudinal waves are typically introduced into the test piece perpendicularly to the composites’ surface. In this spatial direction, their propagation velocity is often quite constant, when looking at the composite from a macroscopic perspective and neglecting, e.g. the influence of locally varying fiber volume fractions or porosity contents (9). As a result, the high complexity of wave propagation in composites only plays a minor role and can easily be controlled with conventional UT technology. This is evidenced by the widespread use of the methods mentioned above to characterize discontinuities in CFRP materials.

Load-bearing composite laminates of several centimeters in thickness are often used for applications in the energy sector, e.g. for wind turbine blades. Their ultrasonic inspection poses new challenges as certain simplifications for the testing of thin composites are no longer valid (10). One way to test very attenuative thick-walled laminates is the use of lower test frequencies, e.g. as for air-coupled ultrasound in the lower hundred-kilohertz range (11). This increases the penetration power of the ultrasonic energy, but negatively affects resolution and sensitivity. Methods that can solve this dilemma are advanced ultrasonic reconstruction techniques such as the total focusing method (TFM) (12) or the synthetic aperture focusing technique (SAFT) (13). Those algorithms allow for consideration of complex wave propagation in anisotropic composite laminates, facilitate a much better spatial resolution, an improved SNR and a higher contrast compared to e.g. phased array (PA) ultrasonics (14-18).

2. CFRP-adapted TFM algorithm

Full matrix capture (FMC) is an ultrasonic data acquisition technique which is mostly conducted with linear PA probes that have $N$ rectangular piezoelectric elements. The elements are often approximated as line sources for cylindrical waves, since their width is usually much smaller than their length (19). In the first firing sequence of the FMC process, element one emits a highly diverging wave front into the test piece which penetrates all volume elements or may be reflected there (see Figure 1a).

![Figure 1. Illustration of the full matrix capture data acquisition technique (a) and the organization of the recorded unrectified A-scan signals in the information matrix (b).](image-url)
Simultaneously, all \( N \) elements record unrectified echo signals \( X_{RF_{ij}}(t) \). These fill the first row of an organizational scheme: the so-called information matrix \( A = A_{(i,j)} \), which is depicted in Figure 1b. The indices \( i \) and \( j \) correspond to the transmitting and receiving elements respectively. When all entries in \( A \) are filled with \( N^2 \) signals, by successively shifting the transmitter \( i \) along the entire active aperture, the full matrix capture acquisition at the current probe position is completed. Once the FMC raw data is stored, any arbitrary beam profile can be digitally recreated, including possible PA inspection patterns and reconstruction algorithms such as SAFT or the TFM (12, 18).

The total focusing method starts by deriving the analytic representation \( X_{a_{ij}}(t) \) from the real-valued recorded signals \( X_{RF_{ij}}(t) \) using the Hilbert transform \( \mathcal{H}(X_{RF_{ij}}(t)) \):

\[
X_{a_{ij}}(t) = X_{RF_{ij}}(t) + i \cdot \mathcal{H}(X_{RF_{ij}}(t)) .
\] (1)

Then, for the 2D case, the desired imaging plane is discretized into a pixel grid \((x_f, z_f)\). For a given pixel or focal spot, a complex-valued signal height is selected from each analytic signal (i.e. for each transmitter-receiver combination) at a defined time \( t \). The intensity value of a pixel in the TFM image

\[
I(x_f, z_f) = \sum_{i=1}^{N} \sum_{j=1}^{N} X_{a_{ij}}(t) = \sum_{i=1}^{N} \sum_{j=1}^{N} X_{a_{ij}} \left( t = \frac{s_1}{c_1(\theta_1)} + \frac{s_2}{c_2(\theta_2)} \right)
\] (2)

is then calculated by summing up the selected amplitude values and finally extracting the signal envelope by deriving the modulus of the complex-valued sum. The times of flight correspond to the wave fronts’ propagation times from the emitter to the current focal spot \( (t_1) \) and back to the receiver \( (t_2) \) (see Figure 2). They are derived via the Euclidian distances \( s_1 \) and \( s_2 \) and the speed of sound \( c \) in the material (12).

Figure 2. Illustration of the total focusing method for a single element combination in a 2D imaging plane. For anisotropic composite laminates, the speed of sound can increase significantly with higher angles \( \theta \).

To consider anisotropic sound velocities in the imaging plane, a function \( c(\theta) \) can be incorporated into the TFM, so that possible reflector signals interfere constructively. Since focusing of ultrasonic energy in composites is influenced by, e.g. the orientation and thickness of individual layers, the multilayered laminate needs to be idealized as a homogeneous but still anisotropic material. Thereby, some accuracy in positioning is lost, which is minimal for thin layers. However, \( c(\theta) \) is now valid at each point of the imaging plane and applicable in the TFM reconstruction (see equation 2). In the literature, experimental (14, 17, 18), analytical (16) and simulative (18) approaches are described to obtain such anisotropic velocity functions for composites.
The divergence angle of a single-element transmission into a composite laminate is much smaller compared to that in isotropic metals (18). Thus, not all volume elements in the inspection area are necessarily penetrated by the transmitted wave front. In other words, it can be beneficial not to use the entire information matrix for the TFM.

Li et al. (14) demonstrated that the SNR of side-drilled holes (SDH) in CFRP laminates can be improved by limiting the angle of wave propagation. For a given focal spot in the imaging plane, a signal from \( \beta \) contributes to the TFM result depending on a maximum reconstruction angle \( \theta_{\text{max}} \). It is defined as the angle between the acoustic axis of the transmitting or receiving element and the connecting line between the considered element and the pixel coordinates. A signal is excluded from equation 2, if the angle of incidence or reflection is greater than \( \theta_{\text{max}} \).

For a given \( \theta_{\text{max}} \), the size of the active aperture \( A_{\text{act}} \) for the TFM process increases with the depth of the current focal spot:

\[
A_{\text{act}}(z_f) = 2z_f \cdot \tan(\theta_{\text{max}}) .
\]

Thus, the number of elements that contribute to the intensity value of a pixel increases with its depth \( z_f \) and can be derived from the element width and pitch of the transducer.

3. Experimental configuration

For the evaluation of the imaging performance of this CFRP-adapted TFM algorithm, a commercial PA acquisition unit from Zetec (Dynaray) and a linear array probe from Olympus (2.25L64-A2) were used to acquire the FMC raw data sets. The 16-bit digitization of the recorded A-scan data was performed at a sampling rate of 100 MHz. The transducer has a nominal frequency of 2.25 MHz and 64 elements with a pitch of 0.75 mm. TFM signal processing was implemented in Matlab.

Two 20 mm thick test pieces made of CFRP and aluminum were used in this study. For both objects, two similar SDH arrangements were defined (see Figure 3). The CFRP laminate was produced in an infusion process and followed a quasi-isotropic layup with 58 woven layers (thus, each about 0.35 mm thick). The center of the probes’ active aperture was always placed above the side-drilled holes.

4. Inspection results

The mechanical parameters of the examined CFRP material are unknown, which is why analytical (16) or simulative (18) approaches could not be used for the determination of the required angle-dependent sound velocity data. Here, the so-called back-wall
reflection method (BRM) (14, 17, 18) was applied to a recorded FMC data set. It is a straightforward experimental way to obtain a set of up to \( N \) anisotropic group velocities (i.e. the velocity of the acoustic energy) of plane-parallel laminates. Figure 4 indicates that the back-wall echo appears at different positions on the time axis, which is exactly at the mid-point on the back-wall between a given transmitter-receiver pair. Since the geometric positions of the individual elements and the laminate thickness \( d \) are known, up to \( N \) angles of propagation \( \theta \) and their corresponding anisotropic group velocities can theoretically be derived. However, it can be challenging to identify the back-wall echo at higher angles due to its low signal amplitude. The highest angle that can theoretically be covered with the BRM depends on the element pitch \( p \), \( N \) and \( d \). In this test configuration, the upper limit was about 50° (14, 18).

Next, the measured group velocities are incorporated into the CFRP-adapted TFM algorithm (see section 2) by fitting a third-degree polynomial function to these data points. To optimize this fit for higher angles, an additional data point at 90° was included, obtained by a through-transmission velocity measurement in fiber direction:

\[
c(\theta) = 2.31 \cdot 10^{-3} \cdot \theta^3 + 0.18 \cdot \theta^2 - 1.99 \cdot \theta + 2972 \quad \text{in m/s.} \quad (4)
\]

According to equation 4, the group velocity values vary between about 3000 m/s at 0° and 6000 m/s at 90°, which highlights the high elastic anisotropy of CFRP.

A TFM result of the CFRP test piece, without limiting the angle of wave propagation, is shown in Figure 5. Note that, only the upper side-drilled hole with a diameter of 3 mm was detected, whereas the two 1 mm SDHs, that are situated below, are shadowed by this larger reflector. In contrast, all three reflectors could be displayed in the reconstruction result of the same SDH arrangement for aluminum shown in Figure 6.
In the FMC data set of the CFRP test piece, the two 1 mm SDHs, located in the acoustic shadow of the 3 mm hole, could neither be displayed in the TFM image nor clearly be noticed in the recorded A-scan data. This finding can be explained by the noticeably smaller divergence angle which a single-element transmission causes in a CFRP laminate, compared to that isotropic metals (18). In terms of axial resolution capabilities at 2.25 MHz, the distance between the vertically aligned holes ($\gg \lambda/2$) would generally allow for their detection in the A-scan data.

Figure 5 also features a prominent horizontal line close to the top surface. This image artifact is caused by clipped (saturated) signals in the proximity of the transmitter pulse. According to equation 1, the Hilbert transform is used to derive the analytic representation of the real-valued recorded A-scan data. A disruption in this data, however, yields to overshoots around the clipped parts in the imaginary part of the analytic signal. The main diagonal of the information matrix, which contains the classical pulse-echo data, and some of the secondary diagonals are especially affected by those corrupted signals. Thus, the TFM image in Figure 5 exhibits a region close to the transducer with excessive intensity values that might obscure possible reflectors.

Similar artifacts may also be produced when inspecting isotropic metals. They are, however, more likely to occur for very attenuative thick-walled laminates, as higher transmission energies are necessary to achieve a sufficient ultrasonic penetration depth.

For the TFM result of the SDH arrangement for aluminum in Figure 6, the directivity function of an array element, radiating into the half-space of an elastic solid, was implemented in the reconstruction procedure (21, 22). This enhanced the overall image quality and tempered the artifact described above. The extracted signal amplitudes were weighted according to the angle of incidence and reflection for each transmitter-pixel-receiver combination with the derived directivity function for the longitudinal mode. Thus, signals from $\theta$ were not excluded from the TFM algorithm, in contrast to the concept of limiting the angle of wave propagation (see equation 3).

Next, the maximum reconstruction angle $\theta_{max}$ was changed from $1^\circ$ to $90^\circ$ with an increment of $1^\circ$ to reconstruct the FMC data set of the CFRP test piece multiple times, i.e. equation 3 was considered in the TFM process. The signal-to-noise ratio of the side-drilled hole was then evaluated for all TFM images as follows:

$$SNR = 20 \cdot \log_{10}\left(\frac{l_{max}}{RMS}\right).$$  \hspace{1cm} (10)
For this, the maximum pixel value of the reflector $I_{\text{max}}$ and the root mean square (RMS) of the noise level, derived from two rectangular areas next to the SDH, were used. The results are plotted in Figure 7. This graph depicts a clear maximum of the SNR at 30° which is 7.3 dB higher than when using all signals in $A$ for imaging, i.e. at 90°. The SNR plot begins to drop from 47° up to higher angles. A similar result was reported by Li et al. (cf. (14)) and demonstrates that applying a maximum angle for the TFM reconstruction can enhance the detectability of small reflectors in composites.

Figure 7. Evaluation of the SNR of a side-drilled hole (3 mm) in CFRP in dependence of the maximum reconstruction angle $\theta_{\max}$ for TFM imaging. The graph peaks at 30° with a SNR of 28.9 dB and is 7.3 dB lower when the entire information matrix is used in the CFRP-adapted TFM algorithm (i.e. at 90°).

Figure 8 shows the TFM image with the peak value of the SNR, i.e. it was obtained with a maximum reconstruction angle of 30°. Note that the small side-drilled holes below the 3 mm reflector still could not be displayed. Also, the high noise level close to the top surface is lower (cf. Figures 6 and 8).

Figure 8. TFM image of the CFRP test piece obtained with a maximum reconstruction angle of 30°. The two 1 mm side-drilled holes below the reflector shown in the image cannot be displayed.

Even though the SNR is optimized by this approach, the image quality of the reflector is negatively affected. This is exemplarily demonstrated in Figure 9, where a periodic triangular pattern in the TFM images is clearly visible at smaller maximum reconstruction angles. It is caused by the concept of limiting the angle of wave propagation. Figuratively speaking, isosceles triangles are defined under each probe element whose tips are pointing at the respective center of each element. If a pixel lies within one or more adjacent triangles, it can only be reconstructed by the associated elements or element combinations. Thus, in some regions of the TFM image, the
derived pixel values of the created triangles superimpose and create triangular shaped imaging artifacts with locally higher and lower pixel values.

Another noticeable feature in Figure 9 is that the size and shape of the reflector differ depending on $\theta_{\text{max}}$. The more elements are involved in the reconstruction, the smaller the reflector appears in the TFM image, since this algorithm has a strong focusing effect, especially in the x-direction.

![Figure 9. TFM images of the 3 mm side-drilled hole in CFRP for four maximum reconstruction angles $\theta_{\text{max}}$. The highest value of the color scale represents the maximum pixel value of the reflector.](image)

5. Conclusions

Modifications of the total focusing method are necessary to properly reconstruct full matrix capture acquired data for composite laminates. One major advantage of this algorithm is, however, its flexibility in terms of adaptability to a present test situation, which allows for consideration of, e.g., complex wave propagation in composites.

Obtaining the angle-dependent sound velocity in composite laminates is a prerequisite to reliably reconstruct reflectors with the TFM. In this contribution, the back-wall reflection method was used to measure this information. Although it is a quick and pragmatic technique, it is only applicable to plane-parallel laminates and thus, mostly suitable for laboratory applications. If the mechanical parameters of the examined CFRP material are known, which is usually the case, analytical (16) or simulative (18) approaches can be used.

The concept of limiting the angle of wave propagation to improve the SNR of side-drilled holes in CFRP by Li et al. (14), was confirmed in this study. However, triangular shaped imaging artifacts are prominent in the TFM image. Additionally, the spatial resolution decreased for lower maximum reconstruction angles, as less signals from the information matrix contribute to the reconstruction process.

The noticeably smaller divergence angle of a single-element transmission in CFRP impeded the reconstruction of small reflectors situated in the acoustic shadow of a larger reflector. This was not the case for the similar SDH arrangement in aluminum.

In contrast to metals, the practical thickness of composite laminates is mostly limited to a few centimeters. Thus, FMC/TFM inspection is usually performed in the challenging near-surface region below the transducer. This is why adaptions of the TFM and related near-surface imaging techniques (see e.g. (23)) are of great importance to enhance the image quality and detectability of small reflectors in CFRP laminates.

References