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# Digitally focused array ultrasonic testing technique for carbon fiber composite structures

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**Abstract**. Composite fiber reinforced polymers are highly promising structures. At present, they are widely used in different areas such as aeronautics and nuclear industries. There is a great number of advantages of composite structures such as design flexibility, low cost per cubic inch, resistance to corrosion, lower material costs, lighter weight and improved productivity. However, composites degradation may be caused by different mechanisms such as overload, impact, overheating, creep and fatigue. Comparing to inspection of other materials some unique consideration is required for testing and analysis. Ultrasound testing is the most common method for inspection of composite structures. Digitally Focused Array Technology is considered as novel approach which enables fast and effective quantitative automatic testing. In this study new methodology of quality assurance of composite structure components based on DFA is performed.

## 1. Introduction

Application of low quality equipment in manufacturing of composite structures that does not provide required accuracy can cause occurrence of defects that decrease physical and mechanical properties of the material. Furthermore, defects can appear because of manufacturing process failures such as impurity of the material surface or other.

The manufacturing process of composite carbon fiber reinforced polymers is very complicated and longterm procedure. Any inconsistencies can affect the integrity and reliability of the component. Performance of a composite is mostly affected by structural discontinuities, especially if they are exploited under special conditions such as high-temperature loading.

There are several methods of quality assurance that can be applied for composite structures. There are different visual, eddy-current, ultrasonic and radiographic techniques. Composites susceptible to manufacturing defects that compromise structural integrity and generally are not visible to the naked eye. Two factors contribute to increase of the need for better method of evaluating the quality. On the one hand, composite materials are usually used in structurally critical areas, such as military, nuclear and aeronautic. On the other hand, application of composites becomes more and more popular and requires faster inspection as well as ability to detect smaller defects [1].

Ultrasonic inspection has become the most widely used technique for detection of internal defects in composites laminates. It is relatively low-cost, highly sensitive and does not cause any additional exposure as radiographic methods. Moreover, radiography often cannot be applied because the material sufficiently absorbs X-Rays.

## 2. Principles of Digitally Focused Array Technique

Nowadays, ultrasonic techniques are usually based on application of phased array transducers. These types of sensors consist of several elements that can generate an acoustic beam. The main principle is to get interference of acoustic waves. It is possible to change delay laws for each element in order to form particular wave front with higher amplitude on given distance from the surface. Thus, there is a focus point within the highest amplitude that enables to detect smaller flaws and flaws with uncertain boundaries. However, for determination of another focus point the operator will have to generate new delay laws which is time-consuming. Also, it will take a lot of separate measurements to build an image of the whole volume of the component.

In this study we propose the methodology of application the state-of-the-art ultrasonic called Digital Focused Array (DFA) [2-3]. The main principle is to generate a separate impulse by each element of the array, one after another (see Figure. 1).

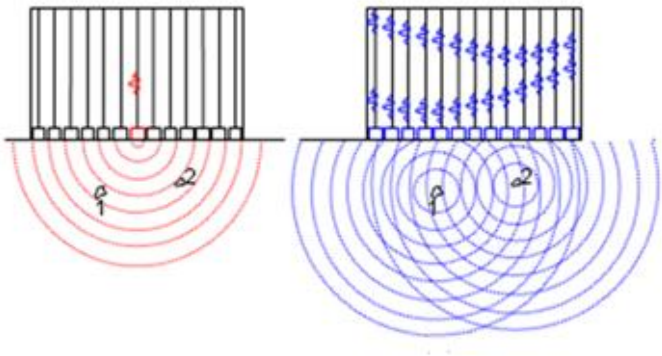


**Figure 1.** Principles of Digitally Focused Array Technique.

Taking into account that an element has a broad beam pattern, generated waves are propagating in all directions. Further, the defects that occur in the material will reflect the wave and will become new sources of secondary waves. Secondary waves are received by all of the elements and form an electrical signal. These signals contain the time of propagation and amplitudes of reflected waves. The achieved signals are then amplified, digitized and filtered in order to get higher signal-noise ratio.

This algorithm is implemented for each element of the phased array, which has a scanning path along the profile in both directions with a given step. The achieved results are used for creating 2D and 3D images of the controlled object.

The resolution depends on the duration of the pulse, dimensions of the array and the velocity of ultrasound. The maximum resolution is half of the ultrasound wavelength.

DFA technique has a number of noticeable advantages such as:

1) Simultaneous scanning on each angle of incident;

2) Possibility to increase resolution by decreasing inspection time;

3) Obtaining reliable results by determining the position of each flaw;

4) The results are generated as 3D images that can significantly simplify interpretation procedure.

As follows, in this study the methodology of quality assurance of composite structures based on DFA algorithm is proposed.

## 3. Experimental Procedure

There are high accuracy and reliability requirements to modern ultrasonic systems, especially to the instruments that are used for testing complex shaped objects. The ultrasonic equipment used for the experiment is demonstrated in Figure 2. The system consists of three main parts: instrumental cabinet unit within the PC (1), immersion tank (2) and robotic manipulator (3).

The scanner performs positioning of the transducer on the given distance from the controlled object.

Correct choice of the transducer is to determine the reliability of testing objects made of different materials and with different geometries.

As it was mentioned earlier, the maximum resolution depends not on the methodology but on the wavelength. Within increasing the transducer’s frequency, the resolution is also increasing, however the control depth gets smaller. The transducer used for the experiment is manufactured by Doppler Electronic Technologies Co., its main characteristics are shown in Table 1.


**Figure 2.** Experimental setup.

**Table 1.** The parameters of the transducer.

| | |
|---|---|
| Frequency, MHz | 5 |
| Number of elements | 128 |
| Element width, mm | 1 |
| Gap between elements, mm | 0.2 |
| Element length, мм | 8 |

The loss of the amplitude of a signal can be caused by scattering or divergence. This entails the necessity to provide accurate setting for the control system.

While testing well-known materials such as steel, for example, the calibration of instrument sensitivity is made by DGS diagrams. DGS diagram consists of curves representing the character of amplitude attenuation within the increase of the defect occurrence depth. These curves demonstrate the amplitude behavior for defects of different dimensions (Figure 5).

In Figure 5 the vertical axis corresponds to amplitude decrease and the horizontal axis represents relative depth measured in the number of transducer near fields.

However, the manufacturing process requires constant change of composite layers’ material that will unpreventably lead to the changes of acoustical properties. That is why for the inspection of composites it is proposed to produce a reference sample according to the given acoustical properties and manufacturing parameters.

There is one major requirement for the reference sample: it is to represent all necessary defects at all possible depth of occurrence. Also, it is preferable for the sample to imitate different geometrical parameters of the controlled object. The first thing that should be taken into account before designing the sample is multiple reflections of the signal from the specimen surface (see Figure 3).

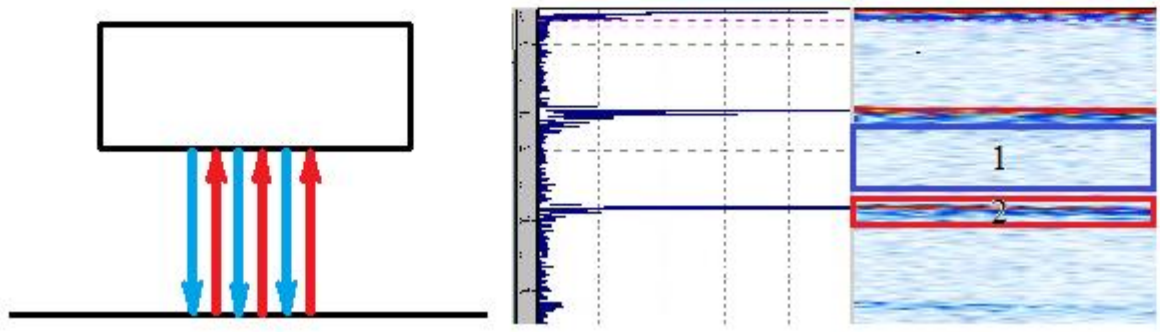



**Figure 3.** Multiple reflections of the signal between transducer and the surface.

This situation may lead to the interference of multiply reflected signal from the surface and signal from the defect that can occur in wrong interpretation. Figure 3 demonstrates that if, for example, defect occurs in zone 1 it will be easily detected, however if the impurity is in zone 2 the operator will miss it.

In order to avoid this problem, the distance between the controlled object and the transducer is to be chosen considering that the time of flight of ultrasound in the coupling material is longer than inside the component. The sound velocity in water is 1500 m/s and in carbon fiber structure it is about 2900 m/s. Thus, the maximum time of flight of ultrasound in the object is:

$$t_o = \frac{2 \cdot h}{2900}, \tag{1}$$

where h is the width of the component.

For generating the second multiple reflected echo behind the back-wall echo, the distance between the surface and transducer is to be calculated according to the following equitation:

$$l > t_o * c = \frac{2 \cdot h}{2900} \cdot 1500 \approx 1.035 \cdot h, \tag{2}$$

where l – distance between the surface of the object and the transducer.

## 4. Results and Discussion

The proposed methodology of composites quality assurance is adjusted on the specified reference sample for system calibration and control samples for the validation procedure.

Delamination is the type of defects that can often be found in composite structures. Delamination is caused by improper surface preparation, inclusion of foreign matter or impact damage during handling [4]. The experimental sample that was used for inspection of delamination is shown in Figure 3 and Figure 4.

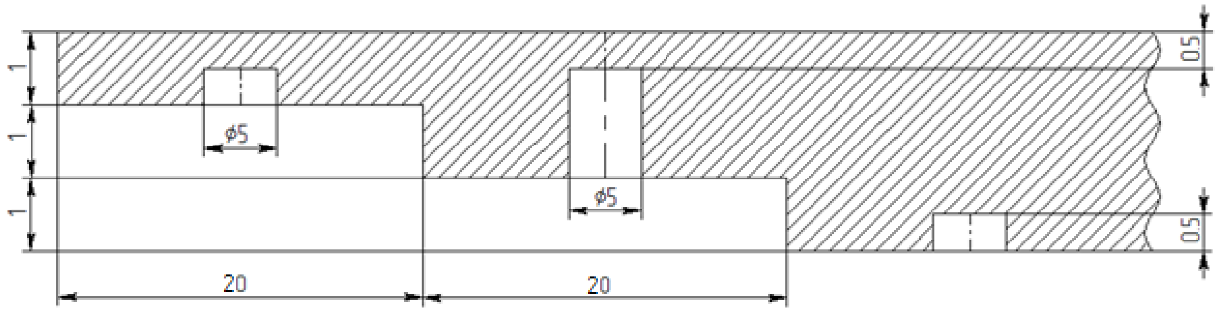



**Figure 3.** Reference sample technical drawing.

The reference sample is made as stepped structure with flat-bottom holes. The step is 1 mm, the length of a step is 20 mm, the diameter of each hole is 5 mm. In order to simulate different defect occurrence depth, the holes are made near the surface or at the bottom. The depth of each flat-bottom hole interchanges in one step. This construction allows to simulate components of different depth and with different defect occurrence depth.

**Figure 4.** Flat-bottom holes on the reference sample.

The calibration of the ultrasonic system requires DGS diagram of the controlled object. For this purpose, it is necessary to determine attenuation of the back-wall echo for different values of depth. In this study the attenuation was evaluated according to the following algorithm:

1) The ultrasound transducer is placed above the first step that corresponds to the thickness of 1 mm;

2) The gain is adjusted in order to achieve 80% of the screen for the back-wall echo (16 dB);

3) The ultrasound transducer is placed above the following step and the procedure is repeated.

The results are shown in Table 2 that contains gain values that are to be chosen for signal attenuation compensation (Table 2).

**Table 2.** Gain values.

| Defect depth, mm | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gain, dB | 16 | 19 | 23 | 27 | 30 | 35 | 36 | 39 | 42 | 44 | 46 |

Taking into account that DGS diagram in the x-point equals to zero we can build DGS diagram (see Figure 5).

For the implementation of this relation time corrected gain was applied. Unfortunately, the software does not allow application of nonlinear time corrected gain. Thus, time corrected gain with constant tilt was applied. It can be shown as a linear correlation graph with the tilt of 3 dB per 1 mm. The measurement results after the correction are demonstrated in Figure 6 below.

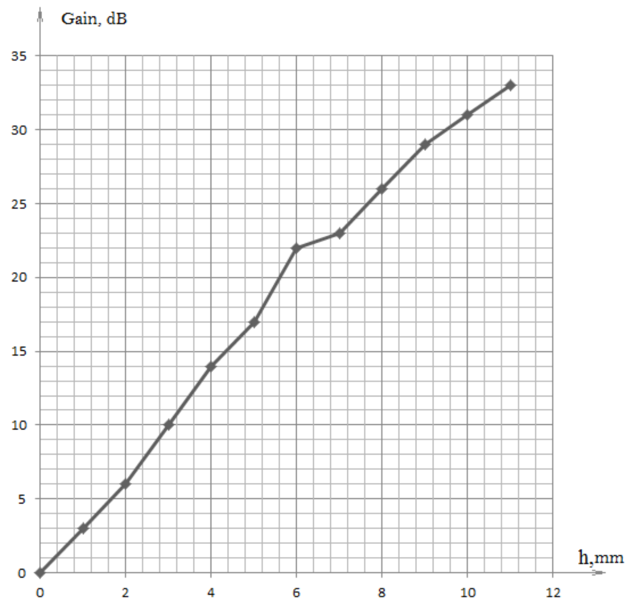



**Figure 5.** DGS diagram of composite component.

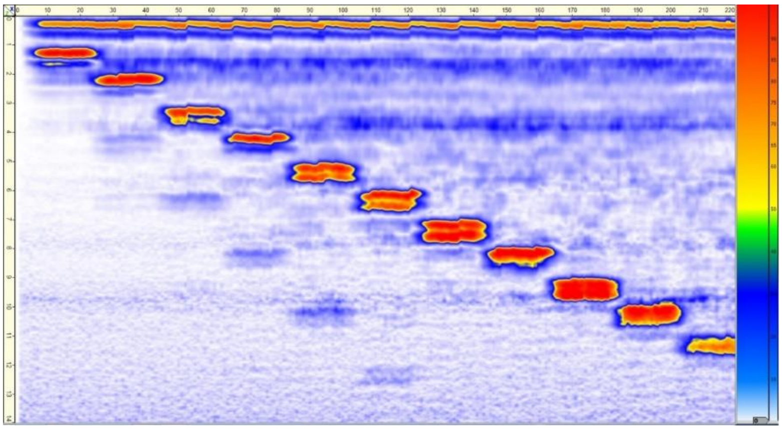


**Figure 6.** The back-wall echo (B-scan).

The inspection of flat-bottom holes is made after the calibration procedure due to the fact, that the back-wall echo is much stronger than the echo from the bottom. Thus the gain is preliminary increased by 3 dB (see Figure 7). The holes near the surface (1), bottom holes and shadows are clearly shown (3).

In order to validate the proposed technique, the experiment of testing the control sample was conducted. The control sample was made with artificial delamination. The results of the experiment are demonstrated in Figure 8 a that represents C-scan and Figure 8 b that represents tomography results. It is quite evident that there are 7 indications that correspond to delamination of the structure.

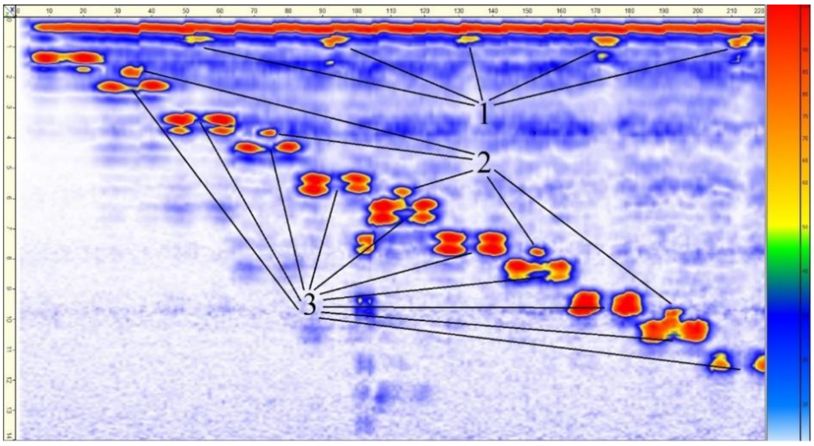
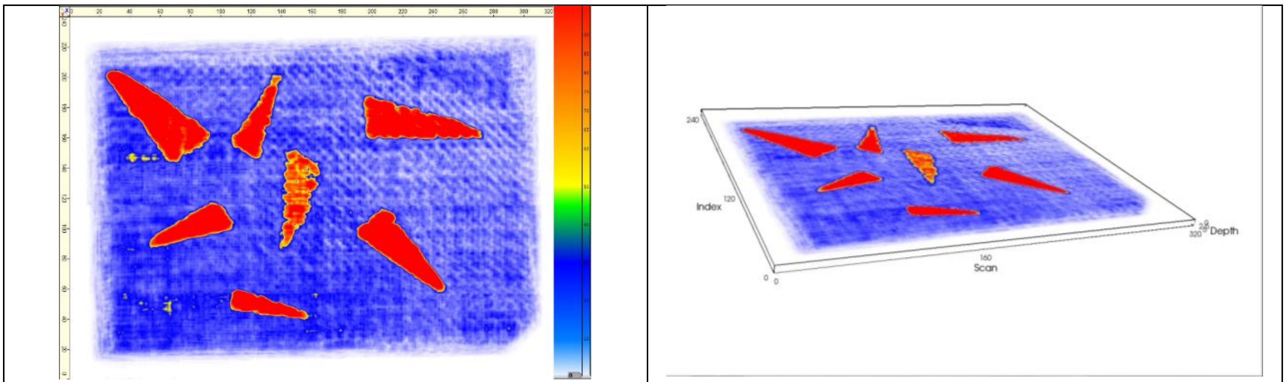



**Figure 7.** Flat-bottom holes' echoes (B-scan).




a) C-scan of experimental results

b) Tomography results of the control sample testing

**Figure 8.** Experimental results.

## Conclusion

In this study the methodology for composite quality assurance is proposed. It is based on ultrasonic DFA technique. The methodology was validated according to experimental results. In further work it is planned to use the suggested technique for testing composite materials produced by additive manufacturing method. Moreover, within the development of high-quality automatic evaluation method it will be possible to create an innovative system for testing complex-shaped objects.

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