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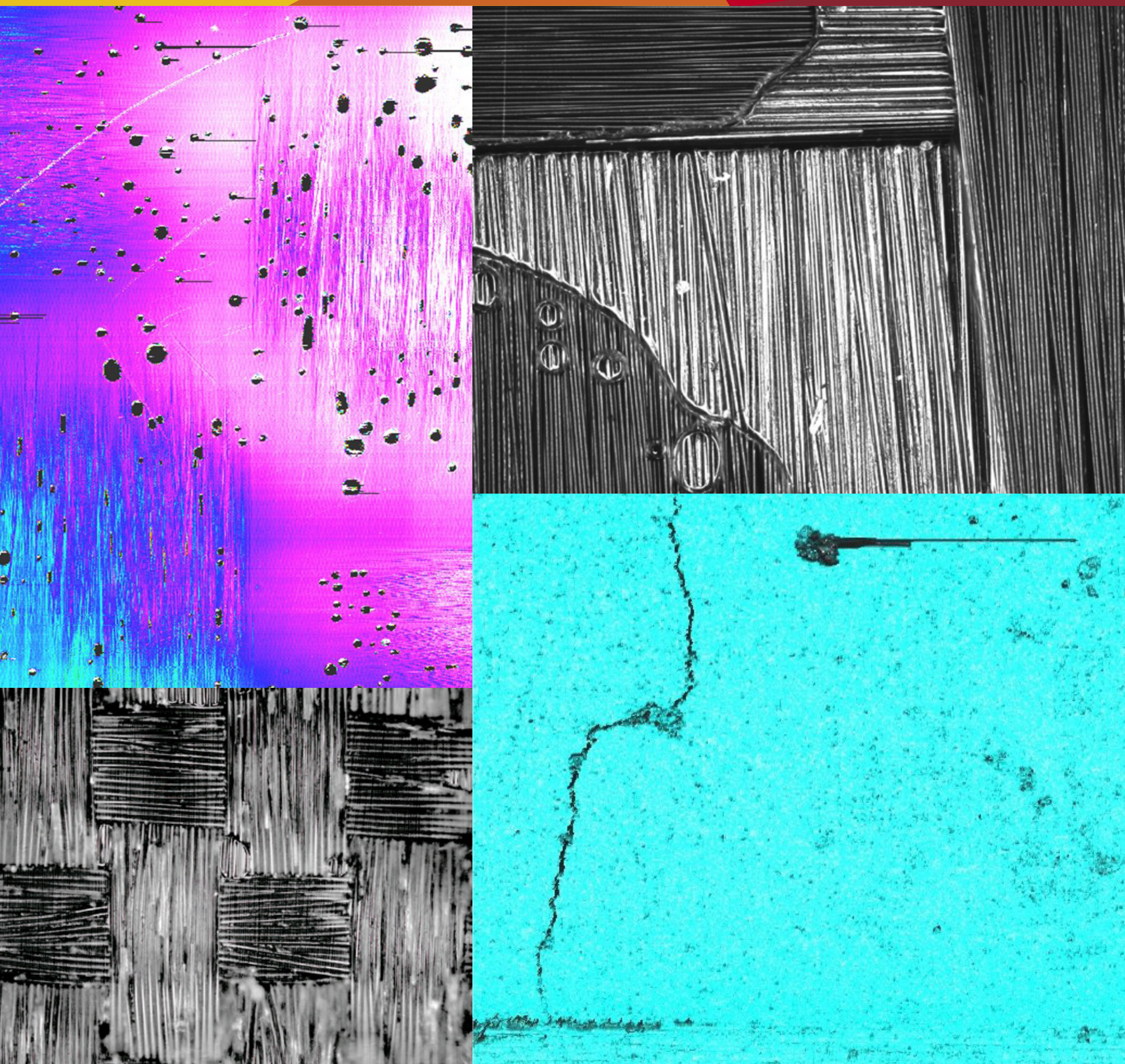
Pauli Vaara • Jukka Leinonen

Technology Survey on NDT of Carbon-fiber Composites



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1 Introduction

This report tells about different non-destructive testing methods that can be used on carbon-fiber composites. *Non-destructive testing* methods, or NDT methods, comprise a broad set of techniques to evaluate the properties of a material, component or system without damaging it. Other common terms that mean the same are *non-destructive examination* (NDE), *non-destructive inspection* (NDI) and *non-destructive evaluation*, but NDT is the one that is used most commonly. NDT methods are highly appreciated in science and industry because use of them can save time and money in research, product evaluation and troubleshooting. /19/

By composite material is meant a material that is made of at least two elements that together produce material properties that are different than the properties of any of the elements alone. Most composites consist of a bulk material, known in this context as the 'matrix', and a reinforcement material. The reinforcement is usually in fiber form and its function is to increase the strength and stiffness of the matrix. The most commonly used types of man-made composites can be divided into three main groups: *polymer matrix composites* (PMC's), *metal matrix composites* (MMC's) and *ceramic matrix composites* (CMC's). /15/

Of these the PMC's, also known as *fiber-reinforced polymers* (FRP), are the most common. Due to their high strength-to-weight and stiffness-to-weight ratios, the FRP's are being used more and more in aircraft and automotive industries. The materials used in various types of components have a polymer-based resin as the matrix; as the reinforcement is used some of the various types of fibers such as glass, carbon or aramid. This report concentrates on the *carbon-fiber-reinforced polymers* (CFRP). /7/, /8/

1.1 NDT METHODS OF COMPOSITES

Non-destructive testing methods that can be used on carbon-fiber composites are different ultrasonic methods, laser shearography, eddy current testing, different X-radiography methods, different thermography methods and acoustic impact. The table 1 below summarizes applicability of some NDT methods for detecting certain types of defects. The rating 0–10 on the table tells the applicability of the method to detect the kind of defect in question. The higher the rating, the better the method works in detecting the defect in question. Not all the methods that are described in this report are included in the table. /15/

Table 1. Applicability of different methods to different kinds of defects. A larger figure means that the method can detect the defect more reliably. /15/

	Acoustic Emission (AE)	Acoustic Impact (AI)	Laser Shearography (LS)	Mechanical Impedance (MI)	Membrane Resonance (MR)	Transient Thermography (TT)	Ultrasonic Amplitude C-Scan (UC)	Ultrasonic Thickness A-Scan (UA)	Ultrasonic Linear B-Scan (UB)	Ultrasonic Depth Scan (UD)	X-Radiography (XR)
Delamination (<10 mm)	7	2	9	4	4	8	9	5	8	9	7
Delamination (>10 mm)	7	5	10	6	6	10	10	8	10	10	7
Crack	7	0	9	0	0	4	0	0	0	0	8
Disbond	2	5	10	6	6	10	10	8	10	10	7
Void	0	1	5	1	1	5	10	6	6	6	10
Impact (BVI)	7	5	10	6	6	8	10	10	10	10	4
Porosity	0	0	8	0	0	6	9	5	6	4	10
Inclusion	0	3	7	4	4	7	9	7	7	6	6
Erosion	0	0	5	0	0	7	7	9	10	10	4
Core splice	0	5	8	5	5	4	6	1	2	0	8
Core disbond	1	10	10	10	10	10	10	8	9	8	5
Core crushing	5	10	5	10	10	5	8	5	5	0	5
Matrix Cracking	10	0	0	0	0	0	0	0	0	0	6
Fibre breakage	10	4	6	4	4	0	0	0	0	0	5
Kissing Bond	0	1	5	1	1	2	1	0	0	0	0
Environment ingress	0	0	4	0	0	10	8	4	5	0	5
Fibre Wrinkling/Waviness	0	0	4	0	0	2	9	1	8	0	2
Fibre and ply misalignment	0	0	2	0	0	2	9	0	1	0	5
Incorrect cure	0	0	0	0	0	0	2	0	5	5	0
Excess resin	0	0	5	0	0	6	5	0	5	8	2
Excess fibre	0	0	5	0	0	6	5	0	5	8	2

10	High	High applicability
7-9	Good	Good applicability
4-6	Medium	Some applicability
1-3	Low	Limited applicability
0	None	No applicability

Various kinds of defects can develop inside composite materials during their manufacturing process. In NDT of composites the defects to be looked for differ from those occurring with metals. Composite materials are heterogeneous, anisotropic and multi-layered structures, and the defects usually occur at the interfaces of the structures. Typical defects include porosities, voids, fiber misorientation, thermal cracks and shrinkage cracks. Some types of defects that are looked for in composite materials are illustrated in figure 1 below. /8/

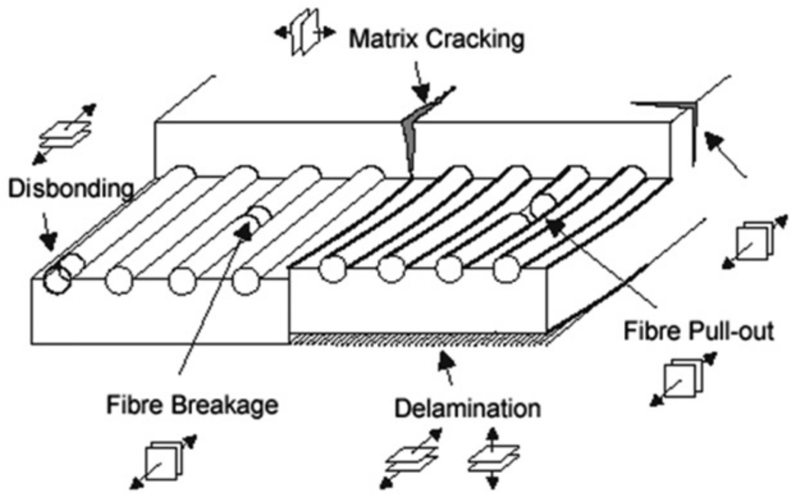

Figure 1. Some types of defects that can occur in composite materials and which are wanted to be detected before they start causing problems. /15/

2 Ultrasonic

This chapter will present eight different ultrasound-based methods for inspecting carbon-fiber composites. These methods are ultrasonic thickness measurement, ultrasonic linear scan, ultrasonic through-transmission amplitude scan, ultrasonic depth scan, acoustography, laser ultrasound, membrane resonance acoustic emission and acousto-ultrasonics. Frequency of ultrasound is higher than 20 kHz.

2.1 ULTRASONIC THICKNESS MEASUREMENT (A-SCAN)

In *ultrasonic thickness measurement*, also known as A-scan, an ultrasonic pulse is first induced into the sample with a probe, and the echo coming back from the sample is recorded with the same probe that serves both as transducer and receiver. Usually a modern measurement device shows on its graphical display either the amplitude or the actual waveform of the signal plotted against time so the operator can draw the conclusions. /15/

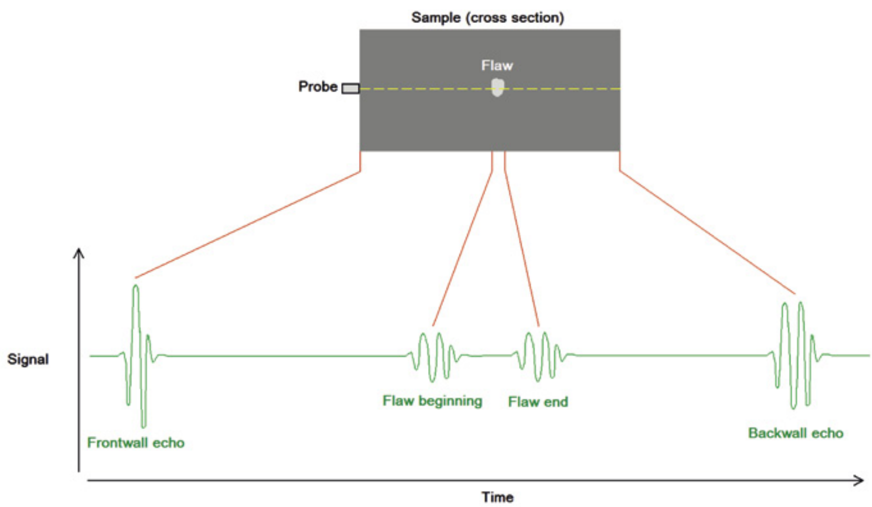

Figure 2. Discontinuities in sample will make ultrasound bounce back, showing as pulses in the signal. /4/

When an ultrasonic pulse comes across an interface between materials in sample, or other discontinuity in it, substantial portion of the pulse encountering the discontinuity will bounce back as echo. The echo of the original pulse will appear as a peak in the amplitude of the recorded signal. In case of a flawless, solid sample there would only be a peak caused by the pulse eventually meeting the other side (backwall) of the sample. But a delamination, disbond, inclusion, planar void or erosion in the sample will produce an earlier peak in the signal, as illustrated in figure 2. If speed of sound in the sample's material is known, the thickness of the sample and/or the depth of the defect can be obtained. /15/

It should be noted that the information the A-scan gives only applies to the specific position where the probe was located during the measurement. Ultrasound also has poorer noise characteristics in composite materials, which reduces the reliability of a single measurement. If more coverage and reliability is wanted, more measurements need to be taken in different positions on the sample's surface, in which case the measurement is effectively approaching to become B-scan, which is discussed next below. /15/

2.2 ULTRASONIC LINEAR SCAN (B-SCAN)

Ultrasonic linear scan, or B-scan, essentially is A-scan performed repeatedly, and presented in a different way. While A-scan is performed on individual positions on the sample's surface, in B-scan the probe is linearly moved while measurements are being made continuously. Echoes from each pulse are shown as thin lines in which different amplitudes are expressed as different intensities at each point of the line. Lines from each pulse are shown on the display vertically, and every new line appears beside the previous one. As result, B-scan will cover the sample more thoroughly, and the graph helps to visualize what is inside the sample. Figure 3 illustrates how B-scan is performed. /15/

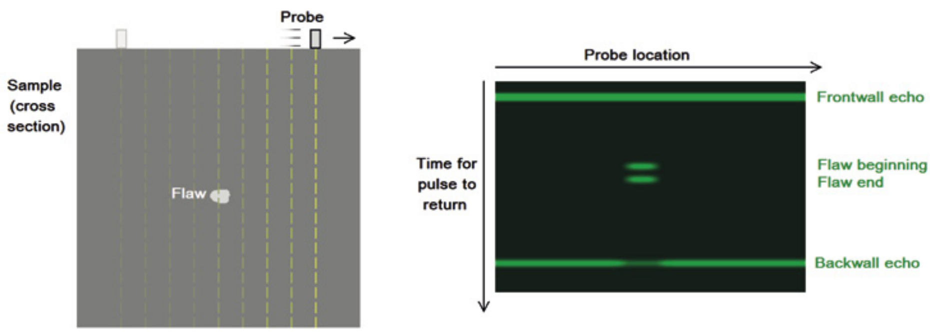

Figure 3. In B-scan the probe is being moved along the sample surface while measurements are continuously being made. The resulting graph will show the echo at different depths in the probe's path. /15/

B-scan can be used for the same purposes as A-scan, but due to the better coverage of the sample through larger number of measurements, the B-scan will give much more reliable results than A-scan. A major use of B-scan besides those of the A-scan, is detecting fiber wrinkling or waviness in aerospace components. /15/

2.3 ULTRASONIC THROUGH-TRANSMISSION AMPLITUDE SCAN (C-SCAN)

As was said above in cases of A-scan and B-scan, discontinuities in sample reflect ultrasound. The stronger the reflections are the less of the signal will go through the sample. In *ultrasonic through-transmission amplitude scan*, which is also known as C-scan, is measured the amplitude of the signal at different points on the sample after the signal has travelled through the sample. C-scan can be implemented with a probe that is moved along the sample surface in a rectilinear raster pattern. However, more commonly the C-scan is implemented with separate transducer and receiver that are being moved along matching paths in opposing sides of the sample. In both implementations strength of the signal after passing through the sample is measured at each spot, and the results are presented as a map showing the signal strengths at different spots on the sample (see figure 4). /15/

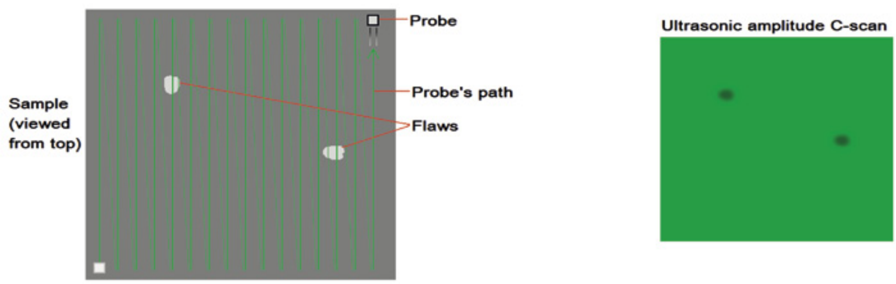

Figure 4. Probe is moved in rectilinear raster pattern along the sample's surface. Attenuation at different points is mapped and shown as the final result from C-scan. /15/

C-scan can be implemented with *through transmission*, or with *pulse-echo* approach, of which the former is more conventional. Both approaches in practice require access to both sides of the sample. When the through transmission is used, the transducer is on one side, and the receiver on the other, so both sides have to be accessible. Also the pulse-echo approach is usually implemented with a reflective plate on the other side of the sample, so access to both sides is needed in that case too. /15/

Either way, the ultrasound requires proper coupling between the transducer, sample and receiver to proceed. Traditionally water immersion or water jet coupling has been used to achieve the required contacts, but nowadays also wheel probes or air-coupled probes are used to simplify in-service inspections. /15/

Types of defects that can be detected with C-scan include:

- delaminations
- disbonds
- voids
- inclusions (contaminants in the sample)
- resin-rich areas
- porosity. /15/

2.4 ULTRASONIC DEPTH SCAN (D-SCAN)

As was said above, ultrasound pulses are reflected by interfaces between materials. In *ultrasonic depth scan*, or D-scan, the probe is moved along the sample surface and a map is produced like in C-scan, but from each pulse is measured the reflected portion like in A-scan and B-scan, not the through-transmitted portion like in C-scan. Due to the method using reflections, it only requires single-sided access to the sample. /15/

In practice a D-scan system measures the time it takes for the echo to return from the first interface after the frontwall in the current position in the sample. Because of this, the method is also known as time-of-flight scan. After the sample has been surveyed with the system, the results will be presented as a map showing depths of the first encountered interfaces in the sample. If there are no flaws in the sample, the pulses will reflect from the backwall, and the map will show just the thicknesses in different points in the sample. Possible flawed points will appear as points that look thinner than they really are; in those points the pulse has reflected from the flaw before reaching the backwall of the sample. An illustration of such measurement can be seen in figure 5. /15/

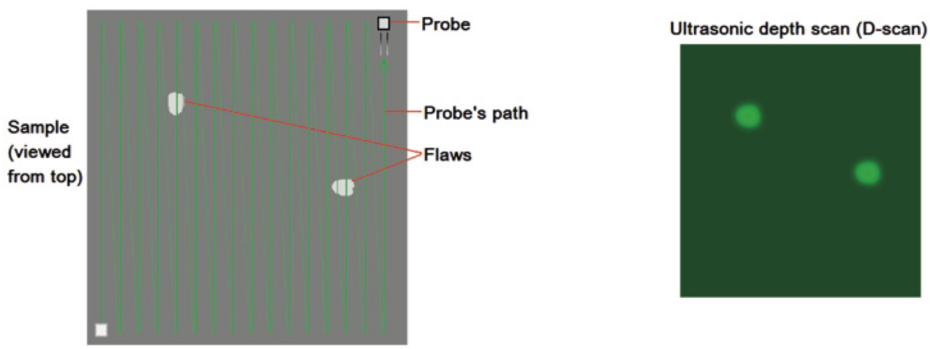

Figure 5. Like in C-scan, probe is moved along the sample surface during the survey. But unlike in C-scan, in D-scan the map will present the depth from which the pulse will reflect in each point of the sample. /15/

Uses of D-scan include detecting planar defects, with which it is better than C-scan. That's because D-scan measures reflection while C-scan measures attenuation, and the planar defects can be better detected using reflection. However, D-scan doesn't suit to detecting as wide range of defect types as methods that measure attenuation. /15/

2.5 ACOUSTOGRAPHY (AC)

There are different ways, or modes, to implement *acoustography* (sometimes abbreviated as AC), of which through-transmission mode and reflective shadow mode are the ones applicable to NDT. In both modes the sample is immersed in a tank with acoustic coupler medium — usually water. The case of through-transmission mode will be discussed here first. /1/, /15/

Through-transmission acoustography is based on the same basic principle as C-scan: on ultrasound attenuating during through-transmission at a faulty spot in sample. The difference between C-scan and acoustography is in the implementation. /15/ In C-scan the measurement system only measures one value at a time, and to form an image, values have to be taken from several spots of the sample by moving the

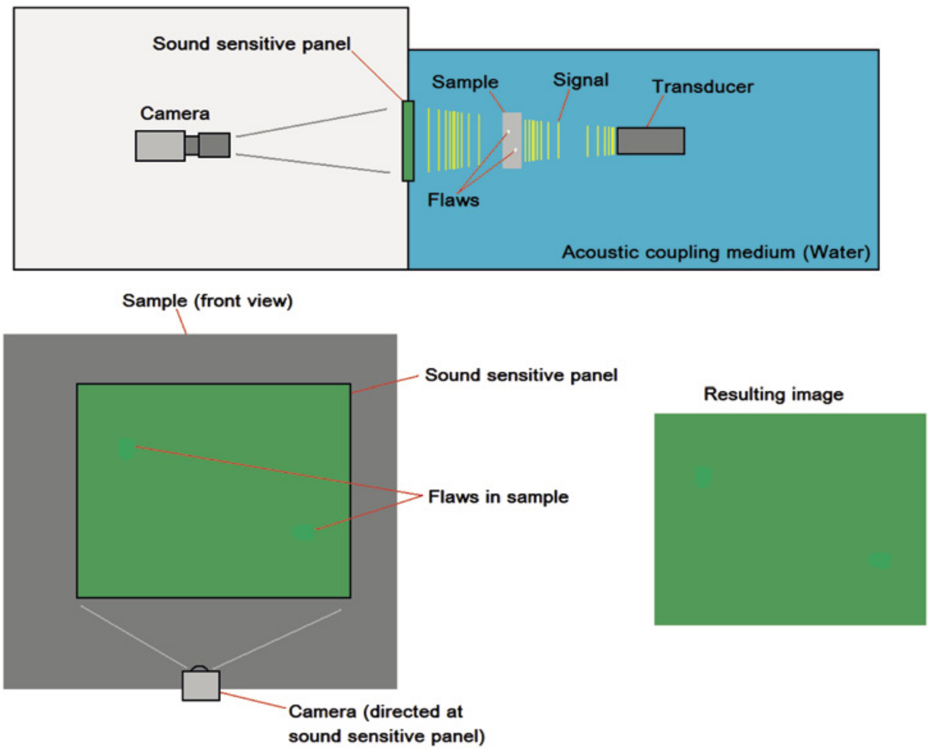

Figure 6. Operational principle of acoustography. In acoustography the sample is immersed in water with transducer and sound sensitive panel. After the signal has passed through the sample, the panel converts the intensities of remaining signal into visible-light intensities that can be imaged with a regular camera.

transducer and the receiver along the sample surface during measurement process. In acoustography, instead, signal generated by transducer is received on the other side of the sample by a panel that consists of spots that can independently react to acoustic energy — similarly as pixels in a digital camera's sensor react to light. Usually the panel covers the area that is to be measured at once. Only if the area is too large for the panel the sample has to be moved during the process. /2/, /15/

Figure 6 presents the functional principle of through-transmission acoustography. A continuous ultrasound signal is created with the transducer to produce a continuous, unidirectional wavefront. The wavefront is directed towards the sample. /2/, /15/ On the opposite side of the sample — usually as part of the tank wall — is mounted sound sensitive panel. Usually the panel is one coated with liquid crystal molecules that change their contrast when hit by acoustic waves. When such a panel is imaged with a camera, a map of attenuations at different positions on the sample is obtained. /15/ Nowadays the sensor can be, besides the combination of liquid-crystal coated panel and a camera, also a panel that directly converts acoustic energy to voltage. /16/ An example of an acoustography system is shown in figure 7. /20/

Since there is less or no need to move the transducer and panel during the measurement process, and since the transducer and panel don't have to touch the sample, acoustography is more suitable for scanning samples with uneven surfaces than C-scan. /15/

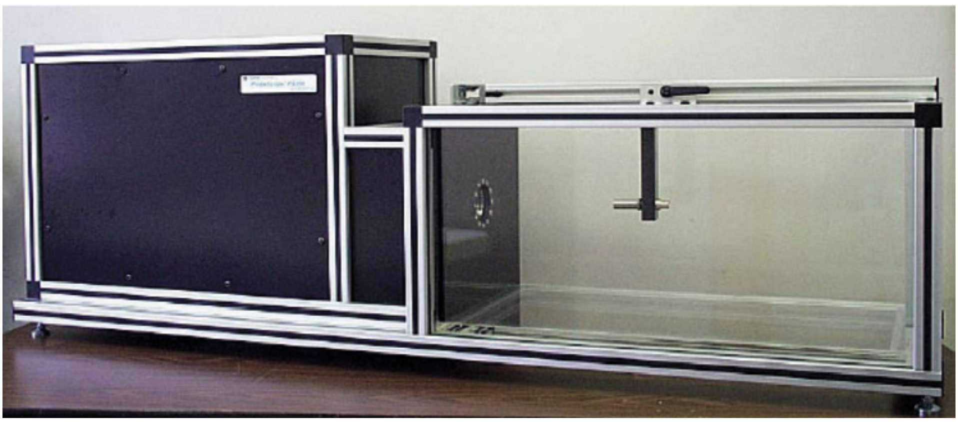

Figure 7. Example of an acoustography system: ProbeScope PS200 by NDT Consultants Ltd. /20/

In the *reflective shadow mode* the transducer and the sensor are on the same side of the sample. In a system using reflective shadow mode the ultrasonic beam is sent to the sample from behind the sensor. The resulting image will show how much the signal attenuated at different spots on its way to the sample's backwall and back to the sensor. Because in the reflective shadow mode the transducer and the sensor are on the same side of the sample, it suits better for testing components while they are in service than the through-transmission mode that requires access to both sides of the sample. /1/, /11/

Like the more traditional ultrasonic methods, acoustography can be used to detect planar defects, e.g. delaminations, inclusions and impact damage. /11/, /22/ A limitation is that the sample has to withstand immersion in water for the measurement. /2/

2.6 LASER ULTRASOUND (LU)

In *laser ultrasound* (LU) method, possible flaws inside sample are detected by measuring how much ultrasound is attenuated in the sample while it travels along the sample. The LU method differs from other ultrasonic methods mostly in that in LU method the ultrasound is generated inside the sample by applying pulsed laser on the sample's surface. /15/ Detection is often carried out with laser as well, but a contacting receiver can be used too. Benefit in the LU method is that it doesn't require contact (if laser is also used for receiving) or immersion. /12/, /15/ This makes the LU method usable e.g. on on-line measurement of hot metal pipes. /17/

Ultrasound can be generated in the sample by supplying pulses with sufficiently high energy to a small area on it. Such pulse will cause quick thermal expansion in the point of laser impact, producing ultrasound. Besides thermal expansion, another phenomenon called ablation can appear too. Ablation occurs if the pulse is powerful enough to heat the impact point over the material's boiling point. When this happens, ultrasound is generated by recoil effect when evaporating material escapes from the sample's surface at the impact point. Usually both of these phenomena take place on each pulse but the power of the pulse determines their proportion. /17/, /18/

After the ultrasound has been generated in the point of laser impact, the ultrasound will travel in the sample the same way as in through-transmission that takes place in C-scan and acoustography. The ultrasound inside the sample will also be conducted to the sample's surface where it will appear as slight vibration. To detect the vibration and hence the ultrasound with laser, most commonly interferometry is used. Other techniques exist as well, some of which are simpler and cheaper by technology but which are less used due to their limitations. /18/

Traditionally the measurements have based on interferometry. In interferometry, laser signal that reflects off the sample surface is compared with reference signal inside the sensor. Phase difference between the reflected and the reference signal is measured to obtain distance to the sample surface. The actual ultrasound is recorded by tracking changes in distance. /12/

An example of other techniques is knife-edge method. In the knife-edge method a continuous laser beam is directed to the sample surface and the beam that reflects from the surface is observed. Position of the reflected beam varies based on the instantaneous distance of the surface. With knife-edge method the actual ultrasound is recorded by tracking the position of the reflected beam. Knife-edge sensors are notably cheaper than interferometers but they are also less sensitive, meaning there can be ultrasounds that are too low in amplitude for knife-edge sensor but that could be still measured with an interferometer. /18/

Besides the laser-based measurement techniques, contacting measurement can be used too. However, then the method is not entirely non-contacting anymore. Touching receiver may have to be used e.g. in cases of too rough sample surface or unusable reflection angle. /12/

When output signal from LU measurement is being interpreted, signal from a single point doesn't necessarily tell much about the sample. But usually LU is used to measure a series of points, and the changes inside the sample will be revealed by changes in the output signal among the points.

In figure 8 is shown a case when the signal-generating laser is being moved from a point to another while the sensor remains in one position. When there's a flaw in the sample, located between the laser impact point and measurement point, the wall of the flaw will reflect back part of the signal. The deeper and steeper the flaw is, the larger portion of the signal will be reflected, and the larger portion of the signal will be missing when it will arrive at the measurement point. When there's no flaw, or when the flaw isn't between the impact point and the measurement point, notably larger portion of the signal will reach the measurement point. However, if there's a flaw near the point of laser impact, the output signal will be wavy because of reflections. /12/

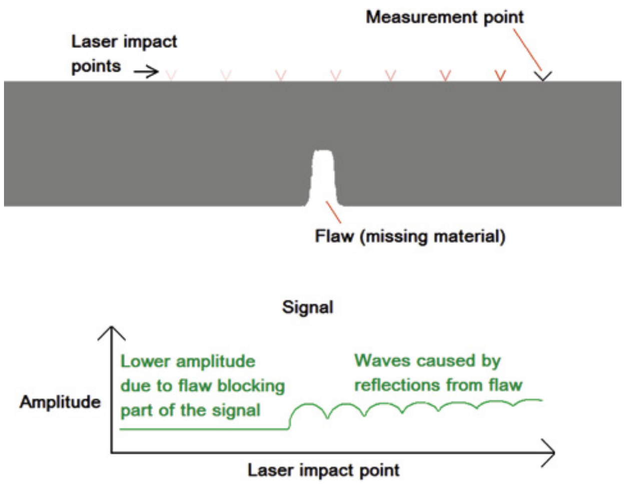

Figure 8. In LU method is measured amplitude of the signal when it arrives at the measurement point. /12/

It's good to notice that testing with the laser ultrasound method is *not entirely* non-destructive: ablation removes some material from the sample's surface, and thermal expansion causes damages in skin-depth below the sample's surface. However, the damages are of microscopic scale, and as such they are negligible in most cases of industrial samples. /18/

Defects that the LU method can detect include delaminations, disbonds and impact damage. To some degree LU method can detect volumetric defects too, including voids and inclusions, but not as well as C-scan could. /15/

2.7 MEMBRANE RESONANCE (MR)

A piece of solid material can be made to resonate by applying ultrasonic waves to it. Thickness of the sample determines the frequency that makes the piece resonate with highest amplitude relative to the applied wave's amplitude. From the technique's point of view, composite material consisting of successfully attached layers counts as solid material. In the context of this method, a consecutive group of successfully attached layers is called a *membrane*. /15/, /16/

In *membrane resonance* (MR) measurement, thickness of the topmost membrane (the one starting from the surface) is measured. In case of a good sample, thickness of the membrane is same as thickness of the sample. But if there is a flaw in attaching the layers (e.g. disbond or delamination) inside the sample, the sample at that point consists of more than one membrane. As the membrane resonance measures only the topmost membrane, in case of a flawed sample the measurement will state that the membrane is thinner at the defective spot. /16/

An example of a system that utilizes membrane resonance method is Fokker Bondtester Model 90, shown in figure 9. It applies ultrasonic signal with rapidly sweeping frequency to the sample, and shows on its screen the resonance frequency and impedance for the sample position in question. Flawed spot in the sample is indicated by change in the values compared to values measured at known good position of the same thickness. /10/, /15/

Figure 9. Fokker Bondtester Model 90 is a bond tester that employs membrane resonance method to test the bonds. /10/

With membrane resonance testing it's possible to detect presence of delaminations and disbonds in carbon fiber composites, and also in other kinds of composites including boron fiber, glass fiber, and fiber aluminum laminates. /10/, /15/

2.8 ACOUSTIC EMISSION (AE)

Acoustic emission (AE) refers to burst of acoustic waves coming from inside the object that is being tested (see figure 10). There are often some levels of divergent forces affecting inside any object, causing stress in it. Usually some amount of stress doesn't have practical effects, but a suitable flaw, e.g. a crack, can change the situation. In position of a suitable flaw, the stress will be relieved in a burst after it reaches a certain level that can defeat the friction between surfaces of the flaw. /15/

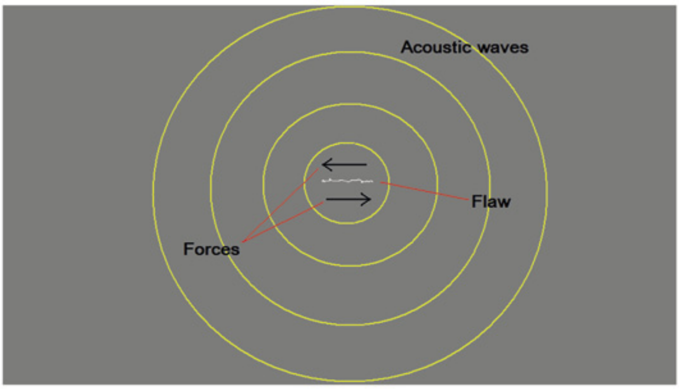

Figure 10. When sufficiently strong forces are pushing surfaces of e.g. a crack to different directions, the forces will defeat friction, and the surfaces jerk a bit to the directions the forces push them to. A consequence from the jerk is a burst of acoustic waves being created. /15/

Naturally, getting some readings from sample requires some acoustic emission to occur during measurement. That's why acoustic emission can't be measured instantaneously, but over some period of time. However, occurrence of an emission can be expedited by applying some stress on the sample. When only a single sensor is used, only the occurrence of the emission can be detected, but using several sensors also the location of the emission's source can be found. /11/, /15/

Acoustic emission can be used to test existence of different kinds of flaws where materials are supposed to be attached but actually aren't, and therefore can move and rub against each other. Types of defects that can be detected with acoustic emission include:

- growth of delaminations
- cracking
- fracture of fibers
- fracture of matrix
- fiber-matrix disbonding
- fiber pull-out
- relaxation of fibers after failure
- large flaws (e.g. interlaminar defects)
- fracture of brittle interfacial layers. /15/

2.9 ACOUSTO-ULTRASONICS (AU)

In *acousto-ultrasonics* (AU) is analyzed how ultrasonic pulses get changed while traveling inside the sample. When performing measurement, broadband ultrasonic pulses are induced in the sample by a transducer that is coupled to the sample's surface. The wave is supposed to simulate acoustic emission being generated inside the sample, but without having to mechanically stress the sample. /15/

A measurement system using acousto-ultrasonics needs to first create a template for each kind of sample that is wanted to be tested. Template is created through learning process for which measurement data needs to be collected from several identical samples that are known to be good. After that, several different features are extracted from the measurement data. Both the time domain and the frequency domain are taken into account in the learning process. /3/

Usually the sensor is coupled to the same surface on the sample as the transducer, a small distance away. To make sure that the measurement data will stay comparable with the template throughout measurements, usually the transducer and sensor are built in same mechanical structure that can be easily positioned on the sample surface as one, keeping the transducer and sensor in correct positions relative to each other. /3/

When measuring pipes, tanks or other objects with longer, unvarying parts, often the transducer and sensor are coupled to the surface with wheels. That way, the AU system can be more easily moved along the sample surface. /15/

Acousto-ultrasonics has been used to measure the following features:

- porosity content
- fiber alignment
- condition of resin
- impact damage
- fatigue damage
- thermal shock
- adhesive bonds. /15/

3 Laser Testing

Laser shearography is a variation of holography specifically designed for NDT applications.

3.1 LASER SHEAROGRAPHY (LS)

A defect decreases the sample's local strength. That's why when a sample with a defect near surface is put under load, the point of the surface located above the defect will deform differently than the rest of the surface. The *laser shearography* (LS) method is based on acquiring surface profile of the sample twice: first while the sample is unloaded, and again while the sample is under load. The difference of the two profiles is obtained, resulting in a fringe pattern. A concentration of fringes means that the material closest to the surface in the corresponding point is subjected to larger strain than in the surrounding area. And this local extra strain means that in such point below the surface the strength is lower than around it. If the whole area that is to be measured is supposed to be of same thickness and consist of same material, the local extra strain hence means that there's a defect below the surface at that point. /16/

To acquire surface profile in the LS method, a phenomenon called speckle pattern is utilized. In the method, coherent light from laser is used to create a stochastic interference pattern that's called speckle. Of the speckle image and a reference image, a shear image is formed. In some LS systems the first sheared image is temporarily stored, and while the loading of the sample is being varied, the system keeps taking new sheared images and shows the difference of the stored and current image on screen in real time. Based on the real-time image the operator can try different ways to load the sample and see if a concentration of fringes would appear somewhere on the surface with any of the ways, as an indication of a weaker point. /15/

Types of defects in detection of which the LS method is at its best are:

- delaminations
- disbonding
- unbonded areas
- impact damage (particularly CFRP)
- planar defects

- erosion (if localized)
- backing / release film containment. /15/

Laser shearography is particularly good in indicating local changes in bond strength, for example to make sure that a patch has attached properly. Other types of defects that could be detected with LS include:

- voids
- inclusions
- excess resin or lack of resin
- gas bubbles and porosity
- near surface imperfections in fiber layout
- local environmental ingress
- excess adhesive
- bond strength. /15/

4 Electromagnetic Testing

4.1 EDDY CURRENT TESTING (ECT)

Eddy current is weak electric current that is induced in conductive material when the material is exposed to a fluctuating magnetic field. In *eddy current testing* (ECT) a coil is placed near the sample's surface, and AC (alternating current) is applied to the coil. Actual measurements can be based on measuring electrical impedance along the coil, or using another coil to measure magnetic field of the sample generated by the eddy current flowing in the sample. Discontinuity in the conductive sample material will decrease the current in the sample, and hence less power will be drawn from the coil. As result the resistance along the coil will be lower as well: resistance is one of the main "ingredients" of which impedance consists, and change in resistance will show in impedance at certain phase. Below in figure 11 is shown how the eddy current acts in the sample. /21/, /5/

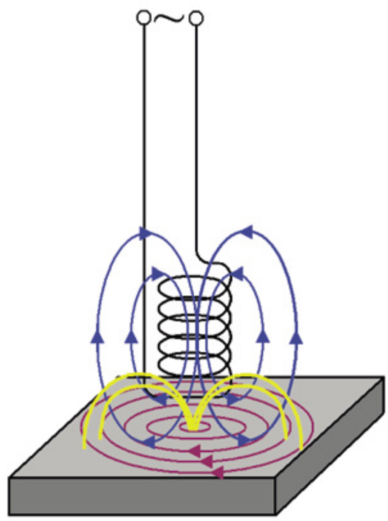

Figure 11. Principle of eddy current testing. With blue is illustrated primary magnetic field that is generated by the AC through the coil. Purple lines show eddy current in the sample material. Yellow illustrates the secondary magnetic field generated by the eddy current. /21/

There are different approaches a probe used in eddy current testing can operate in. These *modes of operation* are often divided in four categories: absolute, differential, reflection and hybrid. /21/

An *absolute probe* has a single test coil with which eddy current is generated in the sample. The actual measurement is performed by measuring impedance along the coil. If the sample contains continuous conductive material, more eddy current will be generated in the sample, which draws more energy from the coil, affecting the impedance by increasing resistance. But if there are discontinuities, the eddy current will be lower, resulting in lower resistance and different-looking impedance curve. Absolute probes are widely used because of their versatility: they can be used e.g. for flaw detection, conductivity measurements and thickness measurements. A weakness in the absolute probes is that their output is affected by several variables while usually just one is of interest when performing measurements. Especially the effect of ambient temperature is commonly compensated using a reference coil built in the probe. /6/, /21/

A *differential probe* has two coils inside it, side by side. The coils are basically like the ones in absolute probe, but the output from a differential probe is the difference between values from each of the coils. Because of this, the necessary compensations take place automatically. As result, a differential probe only shows *changes* in material or its thickness. For example if a sheet that was supposed to be of even thickness everywhere would be flawed with a thinner area somewhere on it, a differential probe would give same values at the normal-thickness area and the thinner area. Instead, at the edge where the thickness would change, the probe would give other values. Also, if the change is very slow and gradual, it might remain unnoticed. /21/

A *reflection probe* has two coils, one of which is used to generate the eddy current in the sample, and the other to sense the current and its changes in the sample. Reflection probes are also called driver/pickup probes, where 'driver' refers to the coil that generates the eddy current and 'pickup' to the coil that senses the current. Reflection probes can have different kinds of coils to generate the magnetic field and to sense the current; because of that both coils can be fitted optimally for their tasks. The driver coil can be large enough to create a strong and uniform magnetic field everywhere around the pickup coil, and the pickup coil can be small enough to be sensitive even for smaller defects. /21/

There are also probes that are based on some kind of combination of the approaches described above, or partly even on some entirely different technique. Such probes are called *hybrid probes*. /21/

Eddy current testing can be used to assess properties of conductive material and presence of defects. In carbon-fiber composites, eddy current measurement responds specifically to the carbon fibers in the composite, which makes eddy current suitable for detection of impact damages, thermal damages and other damages that affect the fibers in the sample material. /6/, /15/

By adjusting the frequency of the AC applied to the coil, depth of penetration can be adjusted. When high frequencies like 50 MHz or above are used, the results will only apply to the top few plies below the sample surface. With lower frequencies the depth of penetration will increase and the results will concern the sample material deeper below surface. That's why low frequencies allow inspection of sandwich structures and other complex components. /6/, /15/

Defects that can be detected with this method include:

- impact damage
- heat damage
- significant fiber breakage
- lack of fiber and conversely excess resin
- localized fiber wrinkling and waviness. /15/

5 X-Ray Radiography

X-radiography methods for the carbon-fiber composites are X-radiography, X-ray tomography and X-ray backscatter. These methods use X-ray, wavelength of which is 0.01–10 nm.

5.1 X-RADIOGRAPHY (XR)

X-radiography (sometimes abbreviated XR) is the most commonly used radiographic NDT method. In it, x-rays are used to take a *shadowgraph* image of the sample, and shades in the shadowgraph show the attenuation to the signal while it has passed through the corresponding spot in the sample. Traditionally films have been used to obtain the shadowgraphs in x-radiography, but use of films wouldn't allow on-line testing. Nowadays x-ray detectors that instantly output the image to computer, making even live viewing possible, are used. /15/

X-rays are attenuated when they interact with energy states of electrons in the atoms in the beam's path. The denser the material is, and the more there is the material, the more the x-rays will be attenuated while traveling through the sample. Therefore, when in a location in the x-ray image the shade is different than in some other location, it means that between the corresponding locations in the sample there is a difference in material density, material thickness or the both. /15/

X-radiography of composites slightly differs from that of most other materials. The reason is that composites are highly transparent to x-rays. That's why rather low-energy x-rays need to be used. If energies that are commonly used when scanning other materials were used, such x-rays would go through the composite sample almost as if there was no sample in place, producing merely saturated images. /15/

To produce the x-rays, device called x-ray tube is used. The energy of the x-rays produced with the tube depends on the acceleration voltage used in the tube. The higher the acceleration voltage is used, the higher will be the energy of the produced x-rays. Respectively, lower acceleration voltages will produce lower energies. Generally suitable acceleration voltage for composites is found in the interval 10–50 kV, but for some composite types the voltage must be between 10–20 kV. /15/

The low energies used with composites require special materials in the measurement equipment; the parts in the x-ray source and detector through which the x-rays go in and out, called *windows*, need to be made of material that's highly transparent to x-rays as well, for example beryllium. Otherwise the low-energy x-rays would be absorbed already in the equipment, leaving insufficient signal for actual measurement through the sample. /15/

There are defect types that can't be seen in an x-ray image, e.g. delaminations and disbonds, especially when they occur laterally, as they typically do. Such defects are virtually invisible to x-rays because they don't change the composition or total amount of materials through which the x-rays travel. However, it is possible to get delaminations and disbonding visible in x-ray image with *radio-opaque absorbent penetrant*. If the defect extends to the sample's surface at some point, fluids with chemicals like diiodomethane, dibromomethane or zinc iodide can spread inside the defect and serve as contrast agent (a.k.a. contrast medium), after which the extent of the damage would become visible in the x-ray image. In cases when the defect is not surfacing at any point, some other technique must be first used to initially detect the defect; after that, if it is possible to inject contrast agent into the found defect, x-ray image can show the extent of the damage by the distribution of the agent in the x-ray image. If depth of the defect is wanted to know, stereoscopic x-radiography can be used. /15/, /16/

Despite the challenges describe above, the primary uses of x-ray imaging of composites comprises detecting cracking and damage associated with impacts, as well as delaminations. A common defect type for detecting of which radiography is used is matrix cracking. However, because of its nature, the x-radiography is best suited to detection of volumetric defects. And it is used increasingly with thick and complex samples, even though with such samples the image quality will suffer. The method can detect following defect types:

- matrix cracking
- cracks
- delaminations
- inclusions
- voids
- porosity. /15/

5.2 X-RAY TOMOGRAPHY (XT)

X-ray tomography (XT), also known as *computed tomography* (CT), differs from traditional x-radiography that produces shadowgraphs in that the resulting images will show cross-sectional 'slices' through the sample. So whereas a shadowgraph would only show total attenuation of the signal between the frontwall and the backwall of the sample, tomography also resolves the attenuation at different points of depth, using data from scanning the sample from different directions. Another benefit with tomography is that slice images resulting from the computation show the sample without geometric distortions, making it possible to measure distances between different points in the sample using the images. Such measurements would not be possible with traditional shadowgraphs where points at different distances from the x-ray source would appear with different magnifications. /15/

When x-ray tomography is being performed, either the sample needs to be rotated in the x-ray beam between the x-ray source and the detector, or the x-ray source and detector need to be rotated around the sample. During the rotation, shadowgraphs are taken of the sample at predetermined interval to collect the necessary attenuation data needed in the computation. /15/

Once the data has been collected from all angles around the sample, images depicting two-dimensional cross-sections will be computed for each slice. Each pixel in a final slice image represents the local x-ray attenuation coefficient at the corresponding point. The attenuation coefficient correlates well with material density as long as the x-ray energy remains unchanged, so the images in practice serve as total density maps for the slices of the sample. /15/

First-generation tomography scanners were based on single-source/single-detector systems. In them the x-ray source transmitted a narrow beam towards a single-pixel detector on the opposite side of the sample. In such a system producing a single slice requires repeating two steps. First the source and detector slide synchronously so the x-ray beam sweeps through the sample. Next the sample (or the source-detector pair) is rotated to the next angle where a new sweep would take place. These two steps are repeated several times, usually until the sample has rotated 180°, at which point coverage of the data would be sufficient to produce a single slice image. /15/

Nowadays usually third-generation systems are used in industry, and with such the scans are faster because there's no need for a separate sweep at each angle. The sweeps are unnecessary because a third-generation system is equipped with a longer detector consisting of several pixels. To collect data for a single slice, the only mechanical movement that is needed is the rotation of the sample, usually again 180° (see figure 12). /15/

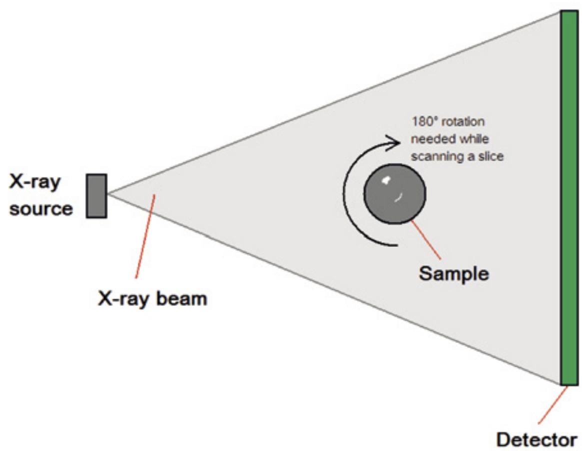

Figure 12. Principle of X-ray tomography with a third-generation system. /15/

What was said above about the special arrangements used in x-ray testing of composites, holds true for tomography as well. Due to composites' transparency to x-rays, such low-energy x-rays are used that other transparent (at least to x-rays) materials need to be used in the equipment in the parts through which the x-rays are supposed to go. /15/

X-ray tomography suits to detecting planar or crack-like defects better than conventional x-radiography producing separate shadowgraphs. This is because in tomography the measurements are performed on the sample from so many angles that there are good chances to have the x-ray beam at some point oriented so the crack will be visible; if the crack shows on input image data, it will have an effect on the resulting slice image too. Tomography doesn't replace the conventional x-radiography in every application because it is slower and more expensive than the normal x-radiography, and because some equipment constraints make it difficult to inspect large or thick components, but tomography has been used to inspect critical aerospace components made of composites. /15/

5.3 X-RAY BACKSCATTER (XB)

The denser the sample material is, the larger proportion of x-rays in the incoming beam it affects by different mechanisms, some of which produce backscatter. The remaining x-ray beam keeps traveling to the original direction unaffected, meaning it doesn't e.g. produce backscatter. In *x-ray backscatter* method (XB) both the x-ray source and the detector are on the same side of the sample, so all the x-rays the detector receives must have been backscattered. If the sample has a point with lower density, larger proportion of the beam will travel through that point without producing backscatter. Unless the less dense point was supposed to be there, the lower value given by the detector will indicate a defect in the point in question. /15/

As said, in the XB method the x-ray source and the detector are both on the same side of the sample. They are also both tightly collimated so that the source outputs the x-rays only in a narrow beam, and that the detector only receives the x-rays from certain direction. While the photons the x-rays consist of travel through the sample, some of them will interact with electrons or other parts of the atoms in the sample material — probability of that depends on the material's density. The photons that don't interact in the sample will continue through it unaffected. /15/

There are several mechanisms for interaction, but the one that is utilized in XB is Compton scattering. In Compton scattering the photons will be directed to other directions when they meet with atoms' electrons. When this happens in the point where the collimation directions of the x-ray source and detector intersect, the photons that happen to be directed towards the detector, will be accepted by the detector. Instead, photons scattering from other points in the sample or ones scattering to different directions won't be detected. Principle of the XB testing is illustrated in figure 13. /14/, /15/

Because the readings only apply to a small volume in the sample, to cover inside of the sample properly, either the measurement equipment or the sample need to be moved in all three dimensions until the sample has been covered to sufficient extent. As result is built a three-dimensional map of the insides of the object. /15/

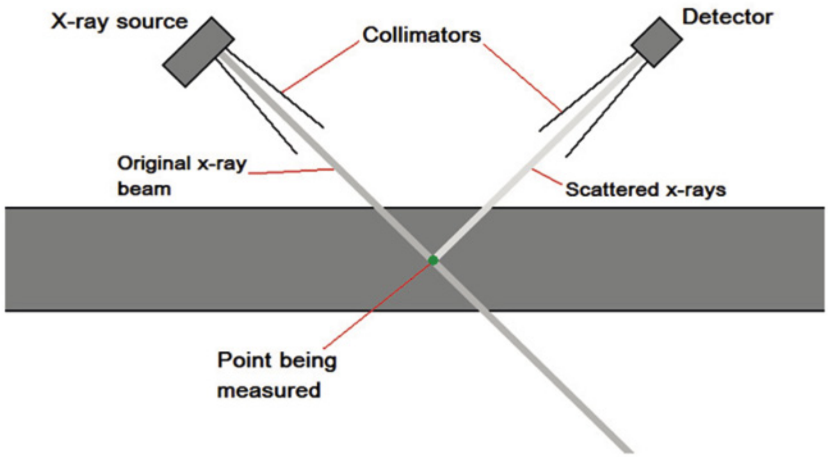

Figure 13. Principle of X-ray backscatter imaging. For readability, only those of the scattered x-rays that are going to the accepted by the detector have been drawn. In reality x-rays would scatter to a range of directions, during all its way. /15/

When working with composite materials, the XB method suits best to detect volumetric defects like voids and porosity. It may also be possible to use the method to detect impact damage, erosion and disbonding. /15/

6 Thermography

Thermography methods used for the carbon-fiber composites are transient thermography, lock-in thermography and vibro thermography. These methods use infrared light which is part of electromagnetic radiation. The wavelength of infrared is 750 nm – 1 mm.

6.1 TRANSIENT THERMOGRAPHY (TT)

In *transient thermography* (TT), which is also known by names *pulse-video thermography*, *pulsed thermography*, *active thermography* and *thermal wave inspection*, heat source is used to heat the surface of the sample and infrared (IR) camera to measure the thermal response of the sample. /15/

The heat source is on for very short time so the heat is generated practically as a pulse. After the pulse image from the IR camera is used to measure surface temperature of the sample over time (see figure 14). This method is an active thermography method

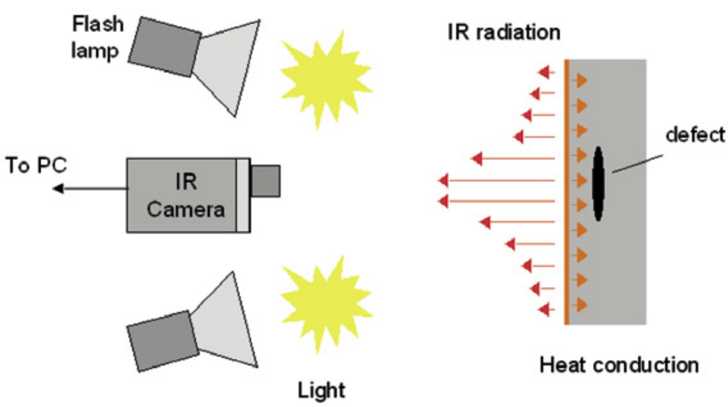

Figure 14. Principle of transient thermography method. A heat source (in this example, lamps) is first used for moment to heat the surface of the sample. After the heating has been finished, the pace at which different areas of the sample's surface cool down is monitored with IR camera. /15/

because heat source is used to heat the surface. The heat source can be a flash lamp, induction heater or hot-air gun. The principle of transient thermography method is that the heat doesn't diffuse as well through a defect as it would through flawless material. When the surface of sample is heated, the heat starts to conduct deeper in the sample, but at defective spot the conduction is slower and the surface remains warm longer. From this follows that when the surface is monitored with IR camera right after the heat pulse, area above defect can be seen to remain warm longer and cool down slower because the heat at there needs some more time to diffuse to the other parts of the sample. /15/

In TT the thermal response of the sample is analyzed to determine the subsurface structure and material properties. Usually the time at which temperature changes take place is more important factor than the absolute temperature change. By temperature-time profile it is also possible to determine the approximate depth of the defect. /15/

The TT method, like thermal imaging applications generally, uses far infra-red wavelength of which is in the range of 3–30 µm. If the IR camera and heat source are built in a scanning system it is possible to inspect large areas such as airframe structures. /15/

As a rule of thumb the optical resolution for defects equals approximately to defect depth in the component. So a delamination of 5 mm diameter should be detectable until 5 mm depth. The method is well suited to the following defect types:

- delaminations
- adhesive disbonds
- impact damage
- density of porosity
- voids, inclusions, foreign objects (provided not thermally matched)
- water ingress, liquid contamination
- corrosion, erosion and localized change in wall thicknesses
- composite sandwich parts for disbonding and liquid contamination. /15/

Conditions that are more difficult to detect include:

- well-matched thermal interfaces
- inclusions of similar material
- optical non-absorbing materials (mirror finish)
- kissing disbonds
- vertical cracks. /15/

6.2 LOCK-IN THERMOGRAPHY (LT)

Lock-in thermography (LT), also known as *phase thermography* is another active thermography method. Instead of single heat pulse the heat source heats the sample repeatedly at a certain frequency of modulation. Using the periodic fluctuations of temperature it is possible to model the behavior of the structure as if the diffusion of heat obeyed the wave equation. Basically the method lets the operator see the delay by which different parts of the image area follow the heat pulsing; differences in delay at some point of the sample imply differences in the sample at that point. /15/

Like in transient thermography, surface temperature of the sample is measured by IR camera. Each pixel of the IR camera records temperature over time, and the temperature data collected by each pixel is considered a separate thermal wave. After that Fourier transform is performed on each of the thermal waves. The Fourier analysis provides magnitude and phase for each pixel, and the magnitude and phase data can be presented as two separate images: magnitude and phase image. The magnitude image is affected by inhomogeneities of optical surface absorption, infrared emission and distribution of optical illumination. The phase image, instead, is not affected by any of these effects. Signal phase also has the advantage that its depth range is almost twice that of signal magnitude. /15/

Eventually the LT method is based on measuring *phase lag*. There is a phase lag between heat source temperature and sample surface temperature. The amount of phase lag depends on the structure of the sample and its thermal properties. The phase lag should give deeper insights into the condition of the sample structure than amplitude data from magnitude image. /15/

LT offers the potential to improve the depth penetration of thermography. Minimum detectable defect diameter is about 10 times the defect depth. For example a defect with diameter of about 200 mm can be detectable at about 20-mm depth. How deep the defects that are searched can be located depends on frequency of the modulation: with lower frequency can be detected defects that are deeper under the surface. /15/

6.3 VIBRO THERMOGRAPHY (VT)

When the sample is excited with high-amplitude sonic or ultrasonic vibration, frictional heating occurs around cracks and other delaminations in the sample. The generated heat can be detected with an infrared camera. The *vibro thermography* (VT) method is also known as *sonic infrared* (or *sonic IR*). /13/ The method suits to detecting the following defect types:

- cracks
- kissing disbonds
- corrosion. /9/

7 Sonic

Sonic method used for testing composites is acoustic impact. Frequency range of this method is 20-20 000 Hz.

7.1 ACOUSTIC IMPACT (AI)

In *acoustic impact* testing (AI) the sample is tapped with an instrumented hammer, making the sample resonate in frequency / frequencies that are characteristic to the sample. The resonance in the sample currently being tested is compared with the resonance that has been obtained from known good sample. Defects in the sample change its frequency response, and presence of defects can be detected by the shifts in the frequency / frequencies. Another mechanism besides the frequency shift that can reveal presence of defects is that the resonance will be increasingly decayed while traveling through a defective spot in the sample. /15/

To perform the measurement, an accelerometer is attached to the sample's surface, or a microphone is used to obtain through the air the sound produced by the vibrations. The frequency response of a sample depends on its size, shape, mass and stiffness. Defects can be detected because they affect the stiffness. If there's a defect in the sample, the change in stiffness will shift the frequency / frequencies the tap makes the sample resonate in. /15/

AI is mainly used in detection of disbonds and delaminations, and it's commonly used on solid composites and composite structures with honeycomb or foam core. The main advantage with AI is that at least in principle a single measurement can detect defects anywhere in the sample. A downside is that the method is not entirely non-destructive, as the tap might do some local damage to the sample. The types of defects AI systems can detect include: /15/

- disbonds between facesheet and honeycomb core
- crushed core due to impact or overload
- voids, inclusions and delaminations in composite repairs
- core splice and thickness change
- potting
- ply drop-off
- doublers, ribs, spars location
- composite repairs on fan cowling, flaps. /15/

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This is a report on non-destructive testing methods of carbonfiber composites. The methods discussed here comprise various ultrasonic, X-radiography and thermography methods; as well as laser shearography, eddy current testing and acoustic impact.

This report includes brief explanations of these methods together with a list of defect types where they can be used for detection. The report is part of NAKOMATE project. The project is funded by Interreg IV A North, Lapin liitto and Länsstyrelsen Norrbotten.

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