

Review And Future of Non-Destructive Testing Methods for Composites in Aircraft

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Abstract. The application of carbon fiber in aerospace requires more advanced non-destructive testing methods due to its unique properties such as anisotropy. In this paper, mainstream non-destructive testing methods are introduced, including visual inspection, resonance test, acoustic emission, eddy current test, ultrasonic test, laser shearography, infra-red thermography, and X-ray. Their strengths and weaknesses are compared, and the common challenges are exposed. To solve those problems, some developing techniques such as hybrid methods and deep-learning-based automated inspection are proposed.

Keywords: Non-destructive testing, defects, composites, ultrasonic, thermography.

1. Introduction

High performance and high reliability are the ultimate goals of aerospace structures. Engineers always seek stronger and lighter materials to enhance the performance and reliability of aircraft. At the age when Wright Brothers invented airplanes, wood was used as the main material to ensure lightness. Around the two world wars, metals like steel and aluminum became dominant for their strength. And now, engineers can satisfy both requirements by using composite materials.

Composite materials have good mechanical strength, low density, low corrosion resistance, and the possibility of manufacturing elements of complicated shapes. In 1963, high performance carbon fiber was discovered, and then Carbon Fiber Reinforced Polymers (CFRP) was invented by embedding carbon fibers in a polymer. Its extraordinary properties and anisotropicness brought the next generation of aerospace materials. With these advantages, Aircraft can be made lighter while stronger, reaching unprecedented speed and fuel efficiency.

Another feature of composite material is the adhesive bond. Instead of riveting or welding, adhesive bonding preserves the integrity of the structure, which saves it from stress concentration. The homogeneous stress distribution eventually leads to higher fatigue resistance.

Due to these advantages, composite materials have been applied to many aircraft with significant weight percentages. For example, the famous Airbus A380 has a composite component at wing roots joint with thickness up to 45 mm. In the latest models of aircraft by Boeing and Airbus, more than 50 percent of the aircraft weight is made by composites [1].

On the other side, carbon composites are more vulnerable to defects. More types of defects can be introduced in composites due to their complex structures. There are multiple ways to engender defects. During manufacture, delamination, foreign object inclusions, porosity, and voids. weak bonds can occur due to human errors and machining anomalies [2,3]. Naturally, fatigue and corrosion may appear. In service, there are impact damages including cracks, delamination, disbonds, etc. Even the low energy or velocity impact like tool drop can cause defects inside the composites. They are called Barely Visible Impact Damage (BVID), which is defined as the damage that is invisible on the surface and cannot be easily detected during visual inspections [4]. Most defects are spawned around the adhesive layer, where two laminates are connected, creating difficulty for detection. Those defects can reduce the residual strength lowering the performance and reliability of the structure, causing catastrophic consequences.

To prevent the failure of composites, defects detection methods need to be developed. Defect detection in composites is more arduous than in aluminum and metal. Not only that the composite is

anisotropic, the different properties between fibers and the matrix, and the depths of composite defects all increase the difficulty of detection. The extensive usage of composite materials requires different standards, techniques, and equipment to ensure safety [5]. One of the testing methods is the mechanical destructive test. Interlaminar Fracture Toughness Energy in mode I and interlaminar shear test (mode II) are the most important destructive tests [2]. They are the only valid ways to evaluate the mechanical performances of the adhesive bond. Yet, since the science community does not have an explicit and complete understanding of the adhesive bond, and since adhesive bonding is a process where conformity of the resulting product cannot be verified, the destructive test is not enough. Securing the safety of one specimen does not necessarily secure the safety of others. A testing method that does not break the integrity of the structure is needed. One way to achieve this goal is through Structural Health Monitoring (SHM). SHM allows the operator to continuously acquire the condition and information of the aircraft. Another way is through the Non-Destructive Test (NDT) or Non-Destructive Evaluation (NDE). NDT is able to detect defects without damaging the structures. Although SHM and NDT have different purposes, the two share many similarities. Some testing methods such as ultrasonic and acoustic emissions are utilized for both. In addition, SHM and NDT need to be worked together; It is critical for SHM to record, analyze, and predict the loading and damaging conditions of the structures so that NDT could be performed in a safe and cost-efficient manner.

This paper will focus on the NDT. Various conventional and nowadays' popular NDT methods will be introduced and analyzed. Their merits and demerits will be compared, exposing some potential problems in the fields. At last, some improved methods and suggestions for the future are proposed.

2. Conventional NDT Methods Review

Until now, numerous reliable and mature non-destructive methods have been developed, and they are widely used in the aerospace industry. In this section, most mainstream testing methods will be introduced: visual inspection, leak test, tap test, fokker bond tester, acoustic emission, eddy current test, ultrasonic test, laser shearography, Infra-red thermography, X-ray radiography and computed tomography. The detailed theory and equations will not be covered, but their comparative strength and weakness will be shown. Section Headings

2.1. Visual Inspection

The visual inspection is certainly the most common, economical, and easiest approach of NDT. According to the Federal Aviation Administration (FAA) advisory circular (AC) 43-294, it is defined as a process of using the eye, alone or in conjunction with various aids, as the sensing mechanism from which judgment may be made about phases of an aircraft life cycle. The inspectors often use tools like lighting, magnifying glasses, microscopes, cameras, and video recording. Due to its simplicity, visual inspection is applied almost continuously from manufacture and production to the flight check and maintenance, repair and overhaul (MRO). Dings, dents, scratches, cracks, pores, voids, corrosion, misalignment, foreign object inclusions can all be detected.

The drawback of visual inspection is apparent. Despite the numerous types of defects, it can detect, it is limited to the surface. It is also subjective: the environment, inspector's sight and status could affect the accuracy of the inspection. The FAA has strict regulations regarding the vision standards of NDT personnel [6]. Yet, the repetitive and tedious inspection process inevitably leads to errors; few of them even caused catastrophic consequences.

More detailed methods and techniques can be found in [5], which provides a general and comprehensive systematic literature review of the visual inspection.

2.2. Resonance Test

The simplest resonance test is the tap test. The inspectors utilize tools like hammers and woodpeckers to tap the surface, generating frequencies around 2 to 16 Hz [2]. By subjectively comparing to the sounds of a reference that is pre-recorded, the defects can be qualitatively observed.

Another method that is more accurate is the Fokker bond tester (FBT). Instead of randomly tapping the surface, the FBT relies on the transducer made of a piezoelectric oscillator that can vibrate at a range of frequencies. The oscillator excites the whole system, and the resonance frequencies are evaluated. Through the adjustment of resonance frequency and amplitude, and comparison between the collected signal and baseline signals, the defects can be detected.

Both methods are rapid and capable of detection in composites, but both are limited by the size of the structures. Tap test is only able to detect surface defects, and the range of FBT depends on the material and frequency needed to vibrate the whole system. In addition, both methods need a reference state, so only the new damage can be detected, which makes them more suitable for SHM.

2.3. Acoustic Emission (AE)

The acoustic emission relies on the damage or defect itself to produce ultrasonic waves. To apply the method, stress or deformation is needed to be subjected to the structure. The stress is usually mechanical loads or thermal stress. The defects would release ultrasonic waves (elastic waves) in response to the stresses and propagate through the material. The piezoelectric transducer eventually picks up the signals. Various defects can be identified through data processing.

Due to the special mechanism of acoustic emission, it is effective to detect developing impact damages including debonding, fiber misalignment, cracks, delaminations. It is also a swift, inexpensive technique that is capable of detecting large areas of internal defects in real time. However, not all kinds of defects can be revealed. It is shown that slow growth of a crack generates a weak AE signal, while rapid crack growth produces a transient signal [4]. This feature also makes AE a competent method for SHM. In addition, its nature prevents the reproduction of the same results. And the most obvious demerit is the applied stress. It must be carefully applied to avoid any damage.

2.4. Eddy Current Test (ECT)

The Eddy Current Testing utilizes a probe coil to generate a magnetic field that will induce Eddy current in the conductive materials. Defects or deformations cause changes in electrical impedance, and with complex analysis and signal processing of impedance, phase angle, and amplitude, damages can be detected.

Eddy Current only works on conductive materials. This feature becomes especially useful when detecting carbon fiber composites such as CFRP. The carbon fiber inside the CFRP is conductive, while the matrix is not. As a result, ECT measurements respond specifically well to the carbon fiber, being able to detect low energy impact damage and heat-induced damage. Because of the nature of Eddy current, ECT is also a fast and non-contact method.

On the other hand, the specialty in conductive material could also be a drawback, limiting the application of ECT. It also has the disadvantages of low penetration, difficulty interpreting the data, and the need to consider the interference factors.

2.5. Ultrasonic Test (UT)

The ultrasonic methods are one of the most adopted and versatile NDT methods. They only require simple equipment and operation but are highly sensitive to the defects, and some methods even have high resolution or large detection areas.

Ultrasounds are defined as sound signals that have frequencies more than 20kHz [7,8]. A vast range of frequencies can be used: higher frequencies have higher resolution and defects sensitivity, but the attenuation rate is also higher, limiting the detection range, while lower frequency has limited resolution.

To conduct an ultrasonic test, an ultrasonic source, a sample, and a receiver are needed. The source would generate an ultrasonic pulse or wave to propagate in the material. The obstacles will reflect or attenuate the signal, allowing operators to detect their existence. The obstacles could be defects, ideally, or they could also be the inhomogeneities and interphases in the composites. Its simple prerequisite led to many techniques. Pulse-echo is probably the most widely used and the easiest one; it uses one transducer along the surface in order to both transmit and receive the signal. This technique is only applicable for a single surface, instead of a large and curved structure. Also, Pulse-echo is proved to be most efficient when detecting defects that are parallel to the surface such as delamination, but not sensitive to perpendicular defects like cracks and fiber fractures [9]. To improve this deficiency, the oblique incidence technique allows the detection of perpendicular defects by inclining the ultrasonic transducer at an acute angle. Immersion based and air-coupled techniques fill the coupling medium between the transducer and sample to reduce the impedance between air and solid. Both have the advantage of low cost and fast scan, but immersion cannot be applied to large structures and have contamination problems, and air-coupled has a low defect sensitivity due to the high attenuation rate. A more costly and rather complex technique, phased array, is capable of solving most problems above. It implements multiple ultrasonic transducers, adjusting the timing and amplitude, and combines the resulting waves. It provides high resolution and high efficiency; with the newly developed methods like the time reversal technique [10] and wheel probe [11], it can compensate for the misalignment between the probe and composite or detect curved edges and narrow components.

On the other hand, ultrasonic techniques have their disadvantages compared to other methods. They are, in general, slower than many other methods, even including the improved techniques above. The detectable depth is limited by the quality of the result due to attenuation. Most importantly, because of the anisotropy and insulative properties of the composite matrix, the ultrasonic waves would be reflected and scattered, creating challenges for the detection ability in composite materials. To compensate for the reflection and reduce the attenuation, lower frequencies are applied, which sacrifice the detection range [12].

2.6. Infra-Red Thermography (IRT)

Infra-Red Thermography refers to the detection of the temperature gradient on the surface with the usage of an Infra-red camera. There are two different kinds of testing methods. One is passive IRT; the testing specimen itself is not in thermal equilibrium: no outside thermal excitation is needed. The thermal contrast and thermal flow will be recorded by the IR camera. Another way is active IRT. Different from passive, active IRT needs outside stimulation. The structure is exposed to thermal excitation, pulsed or periodic, to induce temperature difference. For both methods, heat diffusion will be monitored and recorded. If no defects are presented, the IR image should look homogeneous and cold due; if defects are detected, the shape of the defects would be approximately shown since the defects alter the thermal flow.

For the active IRT, there are two main techniques: pulsed and lock-in thermography. Pulsed thermography emits short, intense heat pulses, while lock-in thermography utilizes a continuous or modulated heat source to keep fluctuating the temperature at a specific frequency. Pulsed thermography has a better signal to noise ratio, but it is limited to surface detection. Lock-in thermography is more suitable for detecting subsurface defects but is more time-consuming.

Overall, the IRT has the advantage of rapidly detecting large areas in a short time or even in real time. Besides, it is a non-contact method, having the potential to be fully automated. Some impact-induced damages like micro cracks have to absorb heat to develop, so IRT becomes an efficient and superior method to detect those [13]. In contrast, the usage of IRT depends on the thermal property of the materials. The detection is restrained to the surface. And the most prominent disadvantage is its difficulty to detect inhomogeneity or hybrid material; the different thermal properties produce different heat diffusivity, resulting in uneven heat distribution, and creating challenges for IRT.

2.7. Laser Shearography (LS)

Laser Shearography is another rapid and contactless detection method. The main mechanism is comparing the two interferometry images using two lasers, captured by the CCD camera: one without deformation and one with deformation. The captured images would appear to have a speckle pattern, called shearograms. Through the subtraction of the two shearograms, a fringe pattern depicting the displacement derivative with respect to the direction of shearing is produced [14], which allows the detection of defects.

There are typically three loadings used to produce shearograms: vacuum, thermal-shock, and vibration. The vacuum loading required the specimen to be sealed in a chamber with a vacuum pump producing negative pressure between the surface and space [15]. The thermal shock or thermal pulse causes thermal expansion or contraction to deform the specimen. The vibration loadings utilize methods like piezoelectric actuators to initiate oscillations or vibrations to create dynamic surface displacement.

LS is a method with great potential. It is extremely rapid, contactless, sensitive, and is able to detect large areas in real time with the capability of being automated. Those advantages have made LS apply to many aircraft including F-22, F-35, Cessna, Airbus, NASA space shuttle, etc. [16]. However, LS is still developing. There are still many problems to be solved. For example, the displacement derivative is less obvious as the detection depth increases; small defects and dynamic defects may not be found; inhomogeneous and absorptive or low displacement materials also hinder the effectiveness of LS.

2.8. X-ray and Computed tomography (XR, CT)

The famous X-ray has applications in various fields, especially in the medical field. The non-destructive testing method of X-ray radiography uses the same principle. The high energy, short wavelength X-ray penetrates through materials. The interaction between the X-ray and materials causes absorptions, transmissions, and scattering, revealing various defects.

One of the useful techniques that use X-ray is Computed Tomography. It can produce detailed images with high accuracy in three dimensions by acquiring the X-ray projections from different angles, and processing and reconstructing them with an algorithm. The processed image provides a comprehensive view of the specimen, allowing the inspectors to identify defects. In addition, Computed Laminography (CL) is a specialized CT technique. With similar principles, CL provides two dimensional images of specific layers, which is particularly useful for composite adhesive layer inspections.

Amongst all methods, X-ray can detect most types of defects, especially the inner, small defects that most other methods have difficulty in. However, XR does have the disadvantages of long inspection time (from scanning to processing to evaluation), expansive equipment, and potential health hazards for the inspectors.

3. Developing Techniques

As stated, many NDT techniques still have the potential to be improved in order to overcome the challenge they face. The improvement could be categorized into three types: individual technique improvement and development, hybrid methods, and machine learning.

3.1. Individual Technique Improvement and Development

One of the biggest issues with composites is that the quality or strength of the adhesive bonds cannot be determined due to the nature of the adhesive and the lack of knowledge. That is partially why NDT grows so important. During manufacturing, the reference composites and their bonds could be tested by destructive methods, various sample tests, and simulations. Yet, Perton et al. suggest that the intrinsic adhesive strength should not be directly compared with the strength given by established destructive testing techniques which solicit differently the bonded assembly [20]. A developing

technique called Laser Shockwave could solve this problem. It relies on the laser-induced plasma to create a shockwave that propagates through the thickness. The wave can be seen as a high tensile strength, and by controlling the intensity, the strength of the adhesive bond can be proved: if the adhesive bond does not reach the desired strength, it will break; otherwise, the shock is harmless. The potential damage it could cause does not necessarily fit it into the NDT category, but it has similar effects. Not only can it determine the quality of the bond, but it also has the potential to detect zero-volume defects like kissing bonds, which none of the traditional NDT could detect. Perton et al. show that the shock is elastic and does not alter the material property [20]. They observe that the shock only propagates in the elastic regime, which confirms the non-invasiveness. Ecault et al. conduct an experiment testing the relationship between shock and shock-induced damage [21]. The laser shockwave technique is still an undeveloped technique. Further research is needed to apply it.

Besides the developing techniques, the existing NDT methods can also be improved. It is known that IRT is difficult to detect heterogeneity and has limited detectability in depth. This could make IRT unsuitable to detect defects for CFRP laminates' interface due to the weak contrast between the thermal properties of constitutive parts, the small thickness of the epoxy joint and the depth of the bonded interface. Barus et al. design a new joint material to enhance the thermal gradients between bonded parts and their defects, similar to the inclusion of marker particles for X-ray [22]. They present that by including a Boron Nitride additive, the conductivity is significantly enhanced. One can easily identify the defects precisely, improving the detection capacity. Similarly, the ultrasonic method has the weakness of multi-layer bonded structures because of interferences and reflections. Li et al. develop a new signal processing method of pulse-echo signal processing based on matching pursuit algorithm to determine locations and size of damages even when the signal waveform is superimposed with noise or boundary, reflection, etc., which increases the readability of multilayer composite ultrasonic signal detection [23]. Bustamante et al. try to improve the ultrasonic method by making it contactless. They successfully utilize air-coupled ultrasonic systems to conduct a non-contact B-scan to identify and characterize the defect on Al and CFRP with an accuracy of more than 80% [24]. Tao et al. try to enhance the detectability of thermal simulated laser shearography by using spatially modulated heat instead of global heat [1,25]. With the assistance of the Finite Element Method (FEM), they conclude that it is possible to improve the detection of the deeply buried defects in the thick composite laminate, but they collect different results when selecting different reference states. It is recommended to use the combination of global heating and spatial modulated heating for better detection while more investigations will be conducted in the future.

3.2. Hybrid Method

Hybrid methods are getting more and more popular in the NDT field. Shearography and Thermography are two of the most hybridized methods. LS needs outside excitation to deform the specimen, and some of the techniques in vibration tests and thermography have already been used for that. Thermography has the advantages of simple implementation and principles, versatility and the straightforward image, so it is often hybridized with other methods. The hybrid methods usually have benefits of enhancing detection sensitivity, reliability, depth and overall range. Due to the complementariness of different methods, the hybrid methods give a more comprehensive inspection.

Acoustic Shearography is an example of a new hybrid method. LS has the advantage of swift and real-time, and the UT has the advantage of large penetration depth. Acoustic Shearography combines their strengths. Instead of conventional vacuum, thermal, or vibration excitation, it utilizes stress loading generated from ultrasonic waves. Zhang et al. conduct a series of tests for Acoustic Shearography and compare the results with X-CT images [26]. It is evident that the wave-based acoustic shearography has sufficiently good defect imaging results with significantly reduced time and large penetration time. Eddy Current Pulsed Thermography is another example. Active thermography needs outside excitation, and Eddy current could be the heating source. ECT is able to generate heat inside conductive materials such as carbon fiber. With the help of ECT, IRT can

overcome its limitation of low penetration depth. Tian et al. conduct numerous tests and show the effectiveness of the method to detect various defects in CFRP [27].

Most hybrid methods are still in their developing stage with relatively low Technology Readiness Level (TRL). Further research and experiments are needed to validate them to increase the versatility and diversity of NDT.

3.3. Automated and Machine Learning

The advancement of Machine Learning (ML) and Deep Learning (DL) gives an opportunity to apply it in the NDT field. Most NDT methods have the features of subjectiveness, difficult image processing, and repetitiveness, which provide a huge incentive for automation. While humans are subjective, prone to errors, and produce varying results, automated inspections are objective, precise, faster and safer. There are certainly some core processes like data evaluation that cannot be replaced, but ML can still be a great tool to double check the validity of the results.

To completely automate the inspection process, the inspection can be divided into three parts: data acquisition, data processing, and defect identification. The data acquisition could be achieved by autonomous navigation by drones or robots. The automated paths can be set by pre-planning methodology and algorithm, or by detection of the natural landmarks from outside the aircraft that are placed around the environment to aid the navigation system [5, 28-30]. The usage of drones replaces the requirement for the human inspector to be close to the object, performing a fast and precise acquisition. Data Processing includes denoising and meaningful features extraction. Autoencoder, a network in DL, is widely used to increase the signal-to-noise ratio (SNR). Munir et al. demonstrate its efficiency by improving 1 and 10% of the defects classification as a result of denoising. Other methods like empirical mode decomposition, principal component analysis, and singular value decomposition can also be used for denoising. The anomaly detection method is used for meaningful data extraction or data reduction. The algorithm could decide what value should be assigned. For the defect's identification, fully connected neural network and Convolutional neural network are used as the network architectures. Numerous experiments are done, showing the capability of detecting numerous defects in metallic structures. Yet, the application of DL on anisotropic material like composites is still challenging due to the anisotropy and layer reflections [31].

Unfortunately, the current implementation of DL-based automation in the NDT field is relatively low among most of the industries. DL is definitely a desired subject to be studied on. The successful implementation of DL could significantly promote the efficiency of NDT, making it more accurate and less time consuming. Industries and regulatory bodies will trust automated intelligent systems when they become widely accepted. More development is needed to automate the NDT methods.

4. Summary

The increasing application of carbon composites in the aerospace industry causes the need to advance the NDT methods due to their unique properties. In this paper, the conventional NDT methods are introduced and compared, and common problems like subjectiveness, difficulty of image processing, and low penetration are shown. Then the newly developing methods, especially the hybrid methods and deep learning are introduced in order to solve those issues. Unfortunately, most of them have a low TRL with slow development. This is partially because of the lack of testing and validation due to the difficulty in acquiring data from the aircraft; manufacturers or regulatory agents usually do not want to share it. Regardless, those new methods are promising, potentially bringing new approaches for NDT.

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