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A Review on Nondestructive Techniques and Characteristics of Composite Materials for the Aerospace System

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Abstract. In the aerospace industry contactless measurement has been a very versatile and adaptable in recent years, mainly because of its diverse applications. Usually ultrasonic measurement requires acoustic contact media which may disserve the sample and varies for different materials. In the operational hand, acoustic contact media like water is also not preferred for on-aircraft inspection. The air coupled inspection technique among other nondestructive testing techniques is often not enticing due to acoustic mismatch and wave propagation. Though, acoustical mismatch of the transducers can be reduced by application of a matching layer and also by using different corresponding transducers. Air-coupled transducers are the captivating alternatives for the inspection. This paper comprises different air coupled inspection techniques i.e. through transmission and guided wave generation as well as its working modes. Various transducer arrangements, the advantages of air-coupled ultrasonic guided wave inspection over other NDT techniques and their specifications are discussed revolving around the materials. Composite materials have superior properties like tensile strength, better heat resistance which cannot be materialized in single. The utilization of composite materials like CFRP, GFRP, other polymers and ceramic composites seeks the improvement in lift to weight ratio. An overall review deals with air coupled techniques and scrutiny of different materials concerning this technique, which includes characteristics of various composite materials used in aerospace industry.

1. Introduction

In contrast to NDT, other tests are destructive in nature and are thereforedone on a limited number of samples ("lot sampling"), rather than on the materials, components or assemblies actually being put into service. These destructive tests are often used to determine the physical properties of materials such as impact resistance, ductility, yield and ultimate tensile strength, fracture toughness and fatigue strength, but discontinuities and differences in material characteristics are more effectively found by NDT.

Non destructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the service ability of the part or system. Non-destructive Testingis one part of the function of Quality Control and is complementary to other long established methods. These methods can be performed on metals, plastics, ceramics, composites, and coatings in order to detect cracks, internal voids, surface cavities, delamination, incomplete or defective welds and any type of flaw that could lead to premature failure. Commonly used NDT test methods along with their respective capabilities and limitation scan be seen in table 1.

Table 1 Commonly used NDT techniques

TECHNIQUES	CAPABILITIES	LIMITATIONS
Visual Inspection	Macroscopic Surface Flaws	Small flaws are difficult to detect, no sub surface flaws
Microscopy	Small Surface Flaws	Not Applicable to larger structures, no sub surface flaws
Radiography	Sub Surface Flaws	Smallest defect detectable is 2% of the thickness; Radiation protection, no sub surface flaws, Not for porous materials
Dye Penetrate	Surface Flaws	No sub surface flaws, Not for porous materials
Ultrasonic	Sub Surface Flaws	Material must be good conductor of Sound
Magnetic Particle	Surface/Near Surface and Layer Flaws	Limited sub surface capabilities; Only of ferromagnetic materials
Eddy Current	Surface/Near Surface Flaws	Difficult to interpret in some application; Only for metals
Acoustic Emission	Can analyze entire structure	Difficult to interpret, Expensive Equipment

Ultrasonic testing using couplants is most popular technique for non destructive testing of solid materials. In the most non – destructive evaluation tasks such as investigation of materials whose properties may be changed by liquid contact, this technique can not be used. Also, when materials under investigation are hot, or when water can fill defects and the detectability of the defects may be reduced. Air – coupled ultrasonic technique is very attractive for non destructive testing and evaluation, because it avoids the disadvantages caused by liquid couplants.

Using air-coupled ultrasound has many great advantages like the complexity in coupling techniques of common ultrasound tests can be avoided using air-coupled ultrasound, as the measurement can be performed independently of the surface nature and any electric conductivity of the body. Additionally, it can be helpful for the measurementof only a few centimetres distance to the object. Coupling problems often occur in the case of a rough surface or if the penetration of liquid couplant should be avoided. On difficult access situations or in-service device testing, Air-coupled ultrasound is the appropriate measurement technique.

2. Significance of Air-Coupled Ultrasound Measurement

The new technology of ultrasonic transducers has been developed that are also able to generate and receive wave transmissions between air and solid transducer. Air-coupled ultrasound (ACU) is increasingly used for automated and contactless inspection of large-scale composite structures as well as for non-destructive testing (NDT) of water-sensitive or porous materials. Air- coupled ultrasound is a contact less measurement method. The transmitted sound wavelengths are above the audible frequency range of humans which is 16 Hz – 20,000 Hz. Sound waves can be reflected, scattered or transmitted.

The applications of air-coupled ultrasonic technique lay in materials with a high degree of inhomogeneity and a high sound attenuation such as CFRP-sandwich components with CFRP and GFRP layers and foam, honeycomb or metallic core materials and even concrete which can only be tested with low frequencies. In spite of the acoustical mismatch using air coupling the indication of defects can be much clearer in comparison with water coupled testing. Compared to conventional contact nondestructive testing methods the advantage of air-coupling is that the inspection can be performed 100 % contact-free. Sensitive materials do not get exposed to couplant liquids such as water, gel or oil. In addition, complicated cleaning processes become obsolete. With air-coupled ultrasound it is possible to detect material flaws and errors in homogeneity. Furthermore, it can be used for the measurement of the thickness, strength and aging of the specimen too [5]. Some of its advantages are:

2.1 Accurate Timing Measurement Using Air-Coupled Ultrasound

Relevant physical properties of a material can often be correlated to the velocity of sound. This can be calculated by measuring the transit time through a reasonably long section of the material. Water would be incompatible with any of the materials (e.g. wood, where properties are significantly affected by moisture). Air-coupled lamb waves lead themselves well to this, since the results are reasonably predictable, there are no coupling arrangements to interfere with production speed, and the experimental setup can often be arranged so that a fairly long distance in the material can be measured, thus minimizing error. Since these applications do not typically require a rapid sample rate, signal processing can be used to further improve signal to noise ratio.

2.2 Large Area Scanning

Through the use of air coupled mechanism comparatively wide range of area of can be scanned for detection.

3.Transducers and Its Arrangements for Air-Coupled Methodology

The probes (transducers) are very important part of ultrasonic NDT instrumentation. The conventional probes are the single one element and dual (double element) probes for longitudinal and transversal waves. According to the direction of the beam axis, there are straight and angle beam probes. Transducers for the generation and reception of sound are without doubt the most critical components of an air-coupled ultrasonic NDE system. Six types of electro-acoustic air transducer types are potentially of interest: electrostatic, variable reluctance, moving coil, piezoelectric, electrostrictive, and magnetostrictive. The through-transmission and pitch-catch configurations are widely used for a variety of applications.

The transmitter generates a wave and the receiver collects it after time delay or attenuation. The measured propagation time and sound amplitudes are converted into digital electric signals by an A/D converter and visualised with a computer. There are three kinds of measurement based on transducer arrangement:

3.1 Normal through-transmission

With normal through-transmission the sound waves of the transmitter hit the surface vertically. The receiver collects the transmitted waves on the opposite side. The incident waves generally depend on the test frequency and the properties of the material

3.2 Shear transmission

In this method, the sound wave hits the object at a known angle and is reflected at the same angle. The receiver collects the transmitted waves at the same angle. The waves react more sensitively to flaws and the elasticity of the specimen with shear transmission.

3.3 One-sided measurement

With some objects it is not possible to place the transmitter and receiver on two different sides. Thus, with the third measurement method, the medium can be measured from one side. However, in this method it is not the transmitted wave that is measured but the reflected. To only receive waves that ran through the medium, a sound barrier has to be placed between transmitter and receiver to shield unwanted and deviated sound waves.

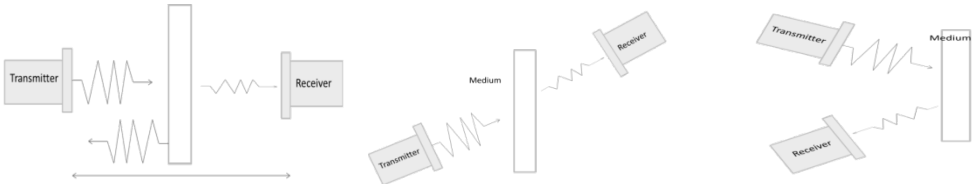

Fig. 1: Transducer arrangement; Normal Through transmission, Shear Transmission and One-Sided Measurement respectively

4. Composite Materials and Its Importance

Various components and structures within aircraft can contain a wide range of materials. These could be metallic (e.g. Aluminium, Steel, Titanium, advanced Alloys such as Inconel); fibre-reinforced composites (carbon fibre-reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP), fibre-metal laminates (Glass Laminate Aluminium Reinforced Epoxy (GLARE), and thermoplastic materials, among others. These can be used either individually, or together, to make up more complex multi-layer or sandwich structures. Depending on the design, these materials are used to realize different functions: fuselage shells, wings, turbine blades, Engine components, helicopter rotors etc. Each part and material under goes a specific manufacturing process, and the appearance of defects has to be avoided.

A composite material is made by combining two or more materials, often ones that have very different properties. The two materials work together to give the composite unique properties. However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other.There are other noticing reasons to pick composites:

- Higher specific strength than metals, non-metals and even alloys.
- Lower specific gravity in general and Improved stiffness & Toughness of material.
- Composite maintain their weight even at high temperatures.
- Fabrication or production is cheaper.
- Controlled Electrical conductivity is possible. Resistant to Corrosion and oxidation

General properties	Mechanical and Thermal	Chemical Properties	Processing Characteristics
• Low cost • Low densiy	• High strength,elastic elongation, High shear strength, High Modulus • Low creep at use temp • High toughness/impact strength • Reistance to thermal degradation • Low thermal conductivity	• High resistance to wear • Good bond to fiber (directly or with coupling agent) • Resistance to solvents & chemicals • LowMoisture absorption	• Low enough melt or solution viscosity and surface tension to pemit • Good flow characteristics • Rapid cure or solidification • Suitable for precoated reinforcement • Cure temperature not greatly above use temperature

Fig. 2: difference in properties of composite materials with reference to other materials

5. Guided Waves and Its Significance

Conventional UT are point to point inspection method ,hence the safety inspection is usually time consuming whereas guided wave is fast and sensitive to small and different types of defects . Guided waves are developed for an effective screening tool useful in locating the defect; thereby minimizing the amount of follow-up inspection needed to determine the integrity of structure. The most promising technique suitable for inspection of waveguide like components (pipes and bars) is based on application of low frequency ultrasonic guided waves.

Ultrasonic waves such as guided Lamb waves, which can propagate large distances in plate-like structures such as composite laminates, provide broader diagnostic coverage than conventional strain sensors for active structural health monitoring of composite structures [1-5].Lamb waves can be generated in composite structures by using an array of piezoelectric transducers, which are either surface bonded or embedded, and exciting with an alternating voltage, which produces contraction and expansion through the piezoelectric effect [6-10].

5.1 Air Coupled Guided Waves:

Ultrasonic guided wave NDT technique which uses Air (not water or gel) as a coupling medium in order to avoid contaminations and damages of the object to be tested is named as Air-Coupled Guided Wave NDT. Well-established conventional air-coupled UT has major shortcoming of weak penetration into solid materials due to impedance mismatch at the air-solid interface that can be sorted by using acoustic mode conversion into guided waves. Several NDT methods like X-ray holography, ultrasonic water squirters, shearography, and acoustic impedance, fails to detect the micro-cracks. But the detection is possible with the air coupled technique using guided plate wave configuration.

6. Related Works

From several years researchers are working to study and enhance the use of air coupled NDT for various applications on several materials. Here are some related works:

In [11], W. A. Grandi et al. have addressed the important key differences between air coupled and liquid-coupled inspection configurations focusing on the practical advantages and limitations that arise from the fact that gases and liquids exhibit substantially different specific densities and sound speeds. The paper portrays the capacities of an industrially accessible air-coupled framework and potential new applications, for example, pulse-echo, in-line assessment and acoustic microscopy. Additionally, a contention is made for investigating the utilization of the recently created micro-machined capacitive transducers as a suitable contrasting option to the at present utilized piezoelectric and past age capacitive air transducers. It also describes the transducer types and circuit topologies that are especially suitable for applications in the 20 kHz to 20 MHz range.

Wolfgang HILLGER et al. [12] mentioned the disadvantages of water coupled ultrasonic testing like pressure variations, air-bubbles, lime scales, algae and corrosion of the mechanics. Therefore preferred a non-contact technique which can avoids these disadvantages. They have presented details of automated scanning i.e. automated air-coupled robot ultrasonic imaging systems for tube-shaped- and flat CFRP- and CFRP honeycomb components. They found In spite of all optimizations the application of echo technique is not possible for the detection of internal defects. Therefore complex geometries require a two sided access for the inspections.

One among the earlier works using this methodology is proposed by M. Castaings et al. [14]. They have described a single-sided ultrasonic NDT system relying on the generation-reception of the A0 mode of Lamb wave. Here, the delamination defects in carbon fibre composite plates have been detected, and the results are efficiently matched with the numerical predictions based on a finite element model

In 2002 another group of researchers had presented the utilization of Ultrasound by its reflection in the air for surface metrology. T.J. Robertson and team in [15] generated an ultrasonic signal in the air with a capacitive transducer to generate a wide bandwidth transient signal. This was then concentrated using an off-axis parabolic mirror onto the perifery of the solid material under test, and the reflection is observed. There work is an excellent example of non-contact surface profiling. The conceivable application outcomes of air-coupled ultrasonic strategy for examination of the Lamb wave propagating in the composite material and the numerical simulation of Lamb wave's interaction with the delamination imperfection were exhibited by Demcenko et al. [16]

In research work by R. Kažys, E. Žukauskas, A Demčenko, L Mažeika along with R Šliteris at the 9th European Conference on NDT (ECNDT) in September 2006 [17]. It has been presented that the scattering-reflection technique is more accurate and is more opt for sizing of defects than the technique with the pitch-catch arrangement of the transducers. A methodology of signal processing has been developed that substantially reduces the influence of the interference of the ultrasonic signals and enables to obtain C-scan images having better resolution and contrast. Air-coupled ultrasonic assessment has been executed in situ. The in-situ measurements demonstrated the high reliability of the air-coupled technique for flaw detection in aerospace composite materials.

R. Kažys and E. Žukauskas by teaming up with A. Demčenko and L. Mazeika extended their investigation of the application of the Air-coupled method for multi-layered composites, presented their research [18] in 2006.Where keeping in mind the disadvantages of pitch-catch method arrangement a new technique of air coupled ultrasonic assessment is described for the detection and visualisation of inhomogeneities in the composite material.

The first experiments regarding ultrasonic materials characterisation interceded by only surrounding air were performed by the physicist Mauri Luukkala and associates from Finland [19] in the early 1970s. Most transducers for Air-Coupled applications at this time operated at KHz frequencies (just above human audible range) and were proposed for movement detection or ranging [20]. The first practical attempts of Air-Coupled transducers initiated with usual piezoelectric devices.

Gordon Dobie et al. in 2011 has presented their work on Simulation of ultrasonic lamb wave generation, detection and its propagation, of a reconfigurable air coupled scanner [21]. A reprogrammable air-coupled ultrasonic scanner was described and evaluated including computer simulator, to ease the design and assessment. The unique scanning system that accommodates a team of remote sensing agents within a shape of miniature robot systems that could reposition non-contact Lamb-wave transducers over a plate type structure for non-destructive testing and evaluation (NDT&E).

In an International Congress on Ultrasonic, Universidad de Santiago de Chile in January 2009, Rymantas Kažys et al. have presented their work on analysis of CFRP rods with the help of Air-coupled guided waves [22].With objective to develop novel NDT technique for aerospace applications using CFRP rods, which rely upon air-coupled excitation and reception of guided waves. By the numerical simulation it was observed that in frequency, ranging up to 0.5MHz at least three guided wave modes propagates: axially symmetric (S0), asymmetric (A0) and torsional (ST).

Since early times, researchers and developers of ultrasonic equipment were making an effort to make the ultrasonic generation transducers sensitive enough to be used for non-contact applications. In this sequence, E. Blomme et al. have presented their experiment performed in the frequency range around 750 KHz to 2MHz. They have examined the possibilities of air-coupled ultrasonics by through transmission-reflection measurement technique as well [23].

Rymantas Jonas Kazys, with Reimondas Sliteris and Justina Stoke in 2015 presented their work on the application of piezoelectric transducer for Air-coupled inspection [24]. Due to very high piezoelectric characteristics of Lead Magnesium Niobate-Lead Titanate (abbreviated as PMN-PT) crystals, they will considerably improve the performance of ACU transducers. Due to these foresaid reasons vibrations of strips and rectangular plates of PMN-PT were analysed. It had been found that potential of the ultrasonic transducer with PMN-32PT crystals were several times higher than that of a PZT primarily based transducers.

7. Conclusion

This paper includes the methods of composite evaluation using NDT techniques by categorizing their advantages and disadvantages emphasizing on the air coupled techniques among other nondestructive techniques which are not enticing due to acoustic mismatch and wave propagation. By reviewing few papers we can say that this acoustic mismatch can be controlled using proper transducers. To conclude the article, importance Air coupled technique and the use over composite materials with various wave propagation and inspection techniques were studied with the aid of reviewing some related works.

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