COMPARATIVE ANALYSIS OF NON-CONTACT ULTRASONIC METHODS FOR DEFECT ESTIMATION OF COMPOSITES IN REMOTE AREAS

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Abstract: There are various ultrasonic systems, developed for the effective testing and estimation of defect parameters in composite materials. Non-contact ultrasonic testing has already achieved significance over traditional contact methods that require coupling of media and are not well suited for the transmission of surface acoustic waves (SAW), which can cover a large area of structure under investigation. This paper compares approaches of air-coupled transmission/reception, laser ultrasonic, and electromagnetic acoustic transducer (EMAT), for testing and verification of composites and defect estimation in remote areas. It reviews the various practical applications. The study found the hybrid solution, consisting of the laser system as a transmitter and the air-coupled method as a detector, is the best among all.

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Introduction

Non-contact ultrasonic testing is a highly accurate and speedy method of analyzing materials and structure without touching the surface. As confirmed by Birnbaum and Auld (1998), ultrasonic testing, performed remotely, does not need direct contact to the area under investigation nor any coupling or glue, and at the same time, does not require any conventional C-scan processes. The non-contact ultrasonic methods can evaluate components and structures on-site to inspect defects, corrosion, cracks, damage, and other impairments in metals and composites. Research performed by Djordjevic (1993) implied that non-contact ultrasonic testing is a successful method of testing surface waves at megahertz (MHz) frequencies to enable defect detection in composite surface layers, because they are highly sensitive to defects and delamination inside composite materials and easily affected by splits, delamination, or inhomogeneity in the structure. Schindel (1997) demonstrated that a non-contact ultrasonic approach can work remotely, with the non-contact test configuration able to be packaged into a compact remote test head.

Non-contact techniques have the ability to generate and detect acoustics with slight modification of the received frequency spectrum, although most systems have frequency limitations. These techniques are appropriate for all kinds of materials, at low to high temperatures, in places that are not easily accessible and situated some distance from the test structure. The most widely used non-contact techniques of non-destructive (NDT) testing are air-coupling, laser generation, interferometric detection, and electromagnetic acoustic transducers (EMATs). The surface acoustic wave (SAW), or Lamb wave, is an effective way to extract information of the test area and identify defects, but is not accessible using conventional ultrasonic transducers. These waves cover large areas and are able to inspect the material at remote locations with higher test speed than conventional contact ultrasonic methods, because they do not need any coupling or contacts for generating or receiving ultrasonic waves (Pierce, Culshaw, Philp, Lecuyer & Farlow, 1997).

There are benefits and shortcomings with each method (EMAT, air-coupled, or laser-based generation/detection). This study aims to compare methods to find the most efficient technique for testing composites in remote locations.

Non-contact Methods

EMAT (Electromagnetic Acoustic Transducer)

The principle operation of an EMAT is based on electromagnetic mechanisms. An EMAT is an ultrasonic NDT method that is contactless because sound waves are generated from within the material, without direct contact with the transducer (Gori, Giamboni, Alessio, Ghia, Cernuschi & Piana, 1996). The EMAT approach is particularly useful for automated inspections in different

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environments. It is an ideal transducer to generate guided wave modes, such as shear horizontal (SH) bulk, surface, and Lamb waves, in materials.

The two basic components of an EMAT are a permanent magnet (or electromagnet) and an electric coil. The magnet produces a static or a quasi-static magnetic field. The electric coil with alternating current (AC) at ultrasound frequency in the range of 20 kHz to 10 MHz also generates the AC magnetic field. Frost, Sethares, and Szabo (1977) and then Dai (1996) confirmed this, in that the interaction of the two magnetic fields produces ultrasonic waves in the test material close to the EMAT.

The EMAT technique has been used with great accuracy in various metals, including tubes, plates, and similar, but one major limitation with EMAT is that, although it is a non-contact technique, it loses sensitivity rapidly as the distance between EMAT and the tested material increases. The other limitation is that EMAT can only evaluate conducting materials, such as metal, in comparison to using ultrasonic waves, which has wider application (Murray & Dewhurst, 2002; Dewhurst, Boonsang & Murray, 2003).

A. Laser generation and interferometric detection

Green (2004) confirmed that methods based on laser generation and detection can perform non-contact ultrasonic measurements of conducting or non-conducting materials, materials at high temperatures, at remote locations and environments where contact is not possible, and when the test surface is a great distance from the laser.

As described by Scruby, Dewhurst, Hutchins and Palmer (1980), the process involves three different mechanisms: radiation pressure, ablation, and thermo-elasticity, for the generation of ultrasound waves using laser beams. The following summarizes the mechanisms:

- The method of radiation pressure is not so critical and has less importance for practical applications.
- During the ablation, slight damage occurs to the surface of the test object, making this method applicable only if there are no other options for generating ultrasonic waves.
- In the thermo-elastic process, the laser pulse absorption occurs, which in turn processes energy in the material up to a finite depth. The thermal expansion changes the mass of the material and consequently, generates an elastic wave.

According to the results obtained by other authors (Monchalin, Heon, Bussiere & Farahbakhsh, 1987; Lanza di Scalea & Green, 1999a), the thermo-elastic process is the most non-destructive of the three mechanisms, and is capable of generating an ultrasonic wave for the required amplitudes. The only limitation of this process is the low sensitivity of the laser interferometer as a receiver, compared with its piezoelectric counterpart. Lanza di Scalea and Green (1999b) also confirmed the use of very bright lasers for generating and receiving enhanced sensitivity, as well as new interferometer designs. Specific methods have also been investigated, such as the narrow-band laser generation, tone-burst signals, and using spatial arrays.

B. Air-coupled generation and detection

The air-coupled ultrasonic method is one of the most common non-contact techniques for NDT. Generally, due to high attenuation, coupling of ultrasonic waves by air is practically impossible, but Grandia and Fortunko (1995) proved that air-coupling is possible at low ultrasonic frequencies.

Previously, Loertscher, Grandia, Strycek, and Grandia (1996) proposed that various available frequencies and digital filters allow optimization in the range between high resolutions for composites and honeycombs (0.5 to 1 MHz) and that required for pultruded materials, such as foam, rubber, tires, and wood is possible (20 to 200 kHz). The key limitation of air-coupled transducers is the high impedance mismatch between air and most materials. Thus, the signal transmission efficiency is quite low, compared to the excitation signal and high-energy input required to feed into the material, and an optimal design of the receiver front-end is required to achieve a good signal to noise ratio (SNR).

C. Hybrid systems

The hybrid systems use the strengths of each technology, as summarized below for three types:

- The hybrid laser generation/EMAT detection system, developed by Oursler and Wagner (1995), has the double advantage of a laser's ability to generate highly-efficient angled shear waves and the capabilities of the tuned EMAT for wave detection. This type of hybrid system is quite economical, as it reduces the cost associated with a full laser system. It also provides satisfactory SNR for defect detection and analysis.
- The hybrid laser generation/air-coupled piezoelectric detection system, proposed by Hutchins, Wright, Hayward and Gachagan (1994), demonstrated the generation and detection of different kinds of waves, such as surface waves and plate waves, using the laser generation and air-coupled detection in metals and fiber-reinforced composites. The pulsed laser point-source in these approaches generates ultrasonic waves, and the resulting ultrasound has a wide frequency range (from 0 to 100 MHz) due to the temporal and spatial confinement of these types of laser sources. Hence, the key feature of these hybrid systems is to utilize the broadband sources and narrowband piezoelectric air-coupled receivers. Wright, Hutchins, Hayward and Gachagan (1996) identified the problem associated with these systems. That is, the bandwidth of the source and receiver are poorly matched and only a small fraction of the energy source is actually detected. This leads to a very low SNR; and to obtain the correct SNR, a constrained surface or ablative source may be necessary.
- There are some other systems based on this approach, and one of these that capitalizes on matching the source and receiver bandwidth was developed by Baldwin, Berndt and Ehrlich (1999). This system produces laser generation of narrowband (~1.2 MHz) ultrasonic waves using spatial modulation. The frequency of the generated ultrasound is used to match the response of a micro-machined, air-coupled, capacitance transducer to achieve high throughput. The system was confirmed as having high sensitivity to surface defects in composites, and being well suited for on-site applications.

Common defects and challenges

Schwartz (1984) describes two ways by which defects are produced in composites. One occurs during manufacture, such as with porosity, which is due to the presence of small voids in the matrix. The second way is through normal-service use of the material over time, such as with failure at the interface between fiber and matrix. Callister and Rethwisch (2007) described these defects, as follows:

- Manufacturing defects: Flaws due to porosity or voids, incorrect fiber volume because of extra or insufficient resins, defective and misaligned fibers, bonding defects, misaligned or cracking ply, and or delamination.
- Normal-service defects: Delamination due to bond failures, cracks, fracture, or buckling of fibers, failure at interface between fiber and matrix, and or moisture damage.

The most frequent manufacturing defects, seen practically, are due to porosity or voids. Among the various normal-service defects, delamination is prominent and practically, it is the most common basis of these defects. Delamination may occur due to fatigue, cracks, impacts, bearing, or similar causes. Smith (2009) wrote that as composites are being used in various applications (even widely used in aerospace, aircrafts, and sports equipment), one has to be careful to determine the type of manufacturing or normal-service defect relevant for the specific application.

Djordjevic (2009) confirmed that the application of composite materials in various structural fields is rapidly increasing, and this emphasizes the importance of assuring structural integrity. Although composites are a primary construction material for aerospace, there remain challenges in optimizing the ultrasonic test procedure and analyzing results for this area due to the complexity of the advanced composite materials with layered/bonded structures. Common ultrasonic NDT methods are unsuitable and often misleading for testing anisotropic and non-homogeneous composite materials. Hence, more robust and practical NDT methods are required for advanced composites.

Application Based Methods

The standard methods for NDT testing must be modified as per requirements to achieve the necessary accuracy and throughput. Researchers have been working to improve the accuracy, in the case of identifying defects in composite materials. Kazys, Demcenko, Zukauskas and Mazeika (2006) and Zukauskas, Cicenas and Kazys, (2005) both observed that the air-coupled ultrasonic technique is quite efficient in detecting the non-homogeneity and delamination type defects in composite and layered materials. In the research performed by Zukauskas and Kazys (2007), the air-coupled ultrasonic method showed substantial effect, when investigating aerospace composite materials with artificial delamination type defects and determining defect size accurately. Kazys, Vladisauskas and Zukauskas (2014) developed wideband air-coupled transducers, which allow tuning of the excitation signal frequency, independent of the surrounding media. As well, their rigid structure allows use of these transducers in high-pressure conditions.

Ultrasonic air-coupled techniques using guided waves are an efficient way of inspecting wind turbine blades. Previous studies have confirmed that access to one side only is sufficient, and direct contact is unwarranted (Raisutis, Jasiunienė & Zukauskas, 2008; Raisutis, Jasiunienė, Sliteris & Vladisauskas, 2008). Ultimately, the geometry of defects can be recognized and it is possible to estimate approximate dimensions of the defects from the ultrasonically obtained images. Jasiunienė et al. (2009) also confirmed that adapted ultrasonic and radiographic techniques give reliable results for NDT testing of wind turbine blades.

The material used in the design of structural parts of commercial airplanes is carbon fiber reinforced plastic (CFRP), and laser-ultrasonic techniques were proposed as the efficient and alternative NDT tools for testing and analyzing these complex-shaped CFRP parts (Campagne, Voillaume & Gouzerh, 2013). During the research performed by Zhou and Sun (2013), C-scan imaging results, using laser ultrasonic testing to analyze the inner defects in aeronautical composite specimens, were also verified. The researchers proposed that the non-contact laser ultrasonic technique is a most efficient and modern NDT method in the aviation industry. A laser ultrasonic application, developed by Zhang, Zhou, and Zhou (2015), monitors and characterizes defects in friction stir spot welding (FSSW) by analyzing reflected and transmitted waves in good-weld and defective areas of welds.

Result and Comparison

The results from review and comparison of all noncontact ultrasonic methods are listed in Table 1.

Table 1: Comparison of Non-Contact Ultrasonic methods

Type	Mechanism	Advantages	Limitations
EMAT	Electromagnetic principle	Contactless Suitable for automated inspection	Liftoff distance Not good transmitters Can only be used for conducting materials
Laser Generation/ Interferometric Detection	Radiation Pressure/Ablation/ Thermo-elasticity	Contactless Can be used for Conducting/Nonconducting Materials Works at high temperature Good in remote environment	Laser needs to be in stable position. Hence almost a laboratory method Low sensitivity of laser interferometer receiver
Air-Coupled Generation and Detection	Acoustic impedance of the two materials	More common Can be used for long distance and cover a large area	Impedance mismatch and high reflection losses High attenuation of ultrasound in air
Hybrid Laser Generation – EMAT detection	Both Laser and EMAT principle (laser as a Transmitter and EMAT as a receiver)	Economical Satisfactory SNR (Signal to noise ratio)	Not good for remote location EMAT needs to be very close to test surface
Hybrid Laser Generation – Air-coupled detection	Both Laser and Air-coupled mechanism Utilize broadband laser sources and narrowband air-coupled receivers	Can be the best method for testing composites in remote area C-scan inspection and Lamb wave tomography Can generate ultrasonic waves from tens of kHz up to MHz	Low SNR (however the spatial modulation technique or constrained source can be used)

Source: Authors

Conclusion

The review of various non-contact testing techniques and their applications reveal the need for alternative methods of transmitting ultrasonic energy to overcome the necessity of traditional coupling and limitations associated with it. Methods are summarized as follows:

- Laser-optical ultrasonic methods are applicable for generating and receiving ultrasonic waves. However, the approach needs stable positioning and is usually laboratory-based. The low receiver sensitivity is the key limitation of laser interferometer.
- Electromagnetic methods (EMAT) are more site-applicable, but only where the EMAT probe can remain within close proximity to the test surface.
- Air-coupled methods are the most promising for use with wider distances and show reliable performance on polymer composites. However, the impedance mismatch between air and test materials is the key limitation of air-coupled transducers. The air-coupled transducers are frequency-limited and are better receivers than transmitters.

Hence, for the remote inspection of composites using the non-contact ultrasound, it is better to use the laser system as a transmitter and the air-coupled transducer as a receiver, which is a hybrid approach. This configuration can be used to test large sections and is the best non-contact method for the remote areas.

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