Evaluation of Electromagnetic Near-Field Measurement Technique as Non-Destructive Testing for Composite Structures

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Abstract. Nowadays there is no viable non-destructive method that could detect flaws in complex composite products. Such a method could provide unique tools to allow engineers to minimize time consumption and cost during the evaluation of various product parameters without disturbing production. The latest research and development on propagation waves introduce micro, radio and millimetre waves as new potential non-destructive test methods for evaluation of mechanical flaws and prediction of failure in a product during production. This paper focuses on recent developments, usage, classification of electromagnetic waves under the range of radio frequency, millimetre and micro-waves. In addition, this paper reviews the application of propagation wave and proposed a new health monitoring technique based on Doppler Effect for vibration measurement in complex composite structures. Doppler Effect is influenced by dynamic behaviour of the composite structures and both are effect by flaws occurred inside the structure. Composite manufacturers, especially Aerospace industry are demanding these methods comprehensively inspect and evaluate the damages and defects in their products.

1. Introduction

Non-destructive testing (NDT) or so called non-destructive and evaluation (NDE) is an inspection technique to detect and locate flaws on the surface or through thickness of an object being tested, also this method is cost effective, high quality results, in-line diagnose [1] and speedy testing while required less operators such as labors or technologists [2]. So to satisfy these requirements, selection of suitable NDT instruments subjected to a number of criteria such as; types of materials forming composite that have different physical properties varies according to the weight fraction of composite constituent [3]; shape, size and types of flaws need to be detected; cost of the technique used for inspection [2, 4-6].

In the last decades composite materials are developing very rapidly and require sophisticated NDT system. NDT systems are able to identify the flaws in composite products such as fiber breakage, inter-phy delamination, crack propagation and overheating without induce stress or damages [7, 8]. Therefore, composite industries are demanding a new NDT system that could predict flaws during production and failure during operation as part as structural health monitoring (SHM) of the critical parts. In addition, it can reduce (up to 30%) of the total cost when compared to that of traditional

NDE [9]. This can be achieved by online monitoring which allows efficient solution to interrogate a wide range of the surface of composite structure [10].

Visual inspection is the most common, cheap and easy NDT [2] propagate wave is the most suitable method to visualize internal damages. Ultrasonic test, eddy current X-ray inspection, radiography, shearography, magnetic particle test [2, 4, 11-13] and terahertz spectroscopy could asses the crack initiation and are able to provide data and properties of a structure in advance [14]. Nevertheless, these methods are limited inspection capability, since, it cannot penetrate deeply inside complex shapes to investigate the defects as well as it represents a time consuming and costly especially for composite parts [15].

On the other hand, laser Doppler vibrometers is a suitable method for vibration measurement and provides good information on the bond joint in a composite structure but could not be employ to predict defects inside composites [14, 16, 17]. Microwave, radio frequency interferometry, millimeter wave and lamb wave [18] are very useful inspections methods and health monitoring systems [19] in providing remote inspection on surface and deep layers of structures [17-19].

This paper reviews current existing NDT methods based on their capacity to evaluate the mechanical defects in composite structures. It also proposes a new technique for inspection and monitoring defects in complex composites after production and during service using a near-field measurement technique based electromagnetic waves.

2. Waves Propagation Inspection Techniques

Near-field measurement technique based waves propagation attracts huge attention from NDT specialists due its deconvolution, reliable and repeatability, such inspection possess high sensitivity to damages providing a feasible solution that might minimize the total test time [20].

Commonly, micro, radio, millimeter waves have a good propagation in a wide range of dielectric composite materials [21]. Nevertheless, other composite materials could inspected by associated with short wavelength [22, 23] or ultrasonic and lamb waves, taking into account wave attenuation according to the properties of the material itself, such as: damping in material, wave dissipation, energy required to transfer the wave and so on [24, 25]. Generally, guided waves that are mentioned herein can be classified into five types namely ultrasonic, lamb, RF, millimeter and micro-waves, all are candidate of NDT. Table 1 shows the advantages and disadvantages and other properties of the mentioned waves.

Table 1. Guided wave properties.

Guided wave	Properties
Millimeter wave [19, 26]	It has the ability to penetrate in all the types of material such as metallic, ceramic and etc., the range of the frequency is start from 10 GHz up to 300 GHz or exceed this limit. It is safe for human being when they expose to.
Ultrasonic wave [18, 27]	Limited to material investigation and provide a minor failure of composite that can be on-line obtained from this method. Cannot interact with the internal structure of high porosity material. The range of frequency is start from 300 MHz to 30 GHz
Radio frequency [28, 29]	It is kind of electromagnetic wave and consider as low cost for tracking and identification for detect crack growth, strain and corrosion
Microwave [29, 30]	This wave excites thermography and sensitive to crack detection. Low attenuation associated with it propagation in dust and smoke, also it is suitable for critical application for dielectric materials and ceramic The range of frequency is from 300MHz to 30 GHz and it reach 300 GHz when associated with millimeter wave.
Lamb wave [31, 32]	It is a type of ultrasonic wave, its propagate in isotropic material. Plate thickness is playing important role of it velocity and propagation (thin plate) because this waves considered as dispersive waves, as well as it can identify the damages may occur in composites

As shown in Table 1, millimeter and micro-wave are the most suitable for defect evaluation due to the unique properties of penetrate most types of materials whether its conductive, dielectric, metallic or ceramic materials. Furthermore, millimeter wave can test objects behind barriers and provides information about the vibration amplitude for the operating objects [17, 33].

3. Electromagnetic Near-Field Health Monitoring Techniques

Vibration is one of the major problems that may affect the global integrity and reliability of composite structures and can lead to a catastrophic defects in the materials [34]. So vibration monitoring during operation plays an important role in terms of in-situ structural health monitoring [30]. There are different types methods to monitor and measure vibration, each one depends on the shape and design of the object [35]. A conventional method for measuring vibration was used by Giurgiutiu [36] is shown in Figure 1, the obtained results is suitable for SHM specially for vibration amplitude and mode shape. For NDT vibration can be calculated via scanning laser vibrometers which used by Ooijevaar et al. [37]. They considered laser vibrometer technique is a fast measurement method comparing with accelerometers which provides more confidence for the vibration analysis.

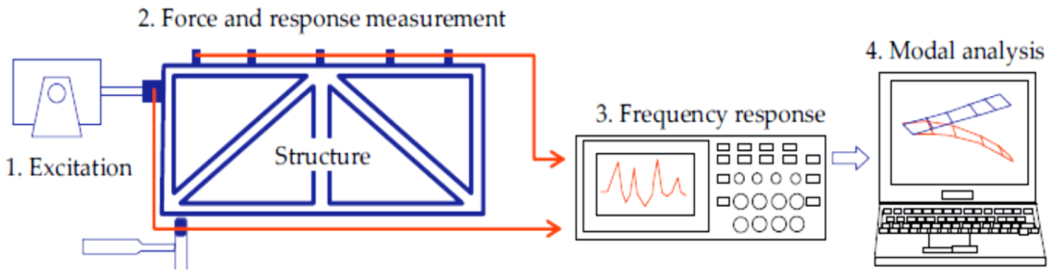

Figure 1. Conventional schematic for model analysis [37]

Continuous wave (CW) which is one of the methods employed for vibration detect (as shown in Figure 2), is contain of two antennas connected to a software, one of them for transmitting the signal and the other for receiving the scattered wave [35]. The scattered wave is the information wave of the phase, frequency and amplitude of the vibration. This wave is proportional to periodically motion of the object. CW method of vibration test is fast and does not need to be connected with sensors to the monitored item. The received signal will be analyzed by fast Fourier transform (FFT) to simulate the mode shape as in the frequency modulation continuous wave (FMCW) approach for vibration measurement and tracking moving objects [26, 38].

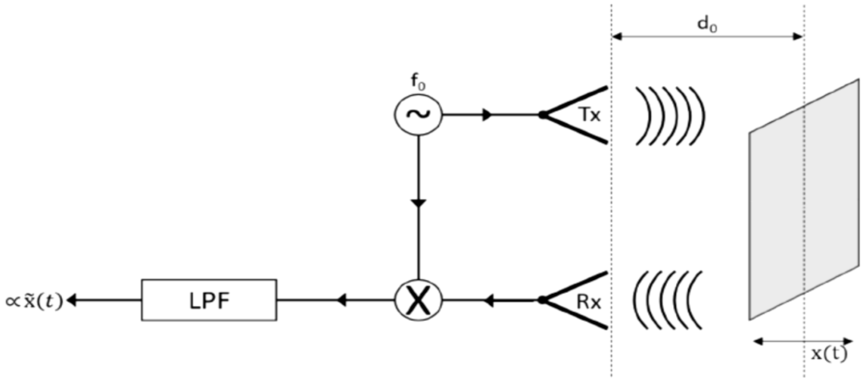

Figure 2. Continuous wave for vibration detect [35]

In contactless vibration measurement method for composite materials, a phase modulation is the key for analysis of vibration as well as wave length associated with frequency domain can control the

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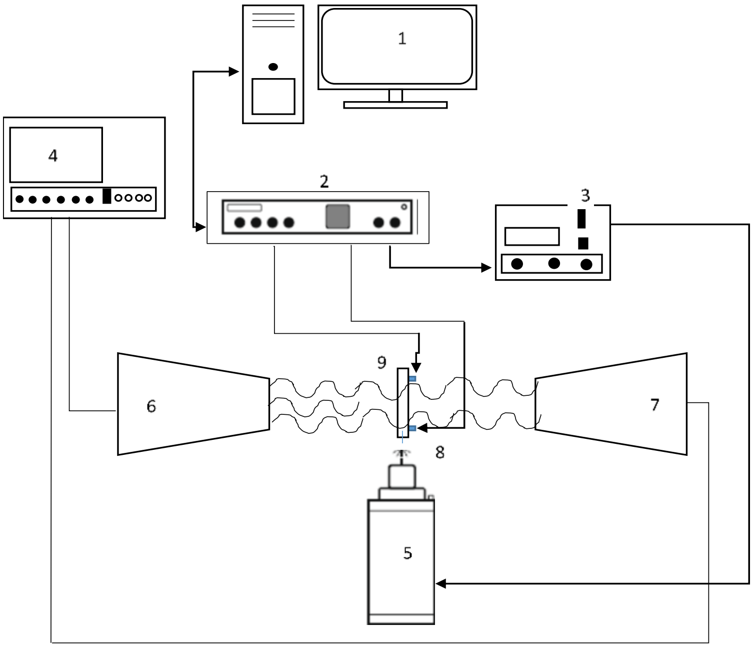
phase modulation [39]. Consequently, Doppler radar sensor is widely used for vibration measurement using this method in a nonlinear mode. The measurement method basically depends on two waves (transmitting and backward), the backward waves received by antenna and go through specific process, the material being tested is a flat plate cover with aluminium foil to enhance better reflectivity [40].

4. Remote Defect Inspection

This study proposes a system where a complex composite structure may be exposed to electromagnetic waves under the range of RF, millimeter or micro-waves. These waves may either be reflected or transmitted through the breadth of product carrying instantaneous stress state information. Such dynamic information can be interpreted to estimate defects and flaws occurrence and evolution under operating conditions.

The system is basically consisting of two antennas one for transmitting and the other for receiving the wave (see Figure 3). The receiving antenna is placed behind the product that is designed to allow for penetration of electromechanical wave. The antennas are connected to a network analyzer [28]. The reflected waves will utilize to detect the vibration amplitude to identify flaws inside a complex composite under operational condition. The transmitted waves on the other side will pass through the product in shifted phase where the phase differences may carry defect information.



No.	Description
1	Computer
2	DAQ
3	Power amplifier
4	Vertical network analyzer
5	Shaker
6	Transmitting antenna
7	Receiving antenna
8	Accelerometer
9	Vibrating object

Figure 3. Vibration and flaw measurement (system conducted in this study)

5. Conclusion

Non-destructive testing was reviewed in terms of classification and properties for each advance method used recently to test composite materials that are developed for aerospace applications. Vibration measurement is one of parameters that plays an important role for the life cycle of a structure. Until to this study, the wave propagation in a material is not fully utilize especially in prediction of failure, crack propagation and delamination of complex composite structures. This paper proposes a comprehensive technique that utilized in operation and/or inspection of the SHM.

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