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Paper SHM 2002-161

A Novel Impedance-based Sensor Technique for Real-time, *in vivo*, Unstable Plaque Characterization

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The most common procedure to treat clogged arteries and restore blood flow in modern medicine is known as Transmural Angioplasy Balloon (TAB). TAB operation consists in inflating a balloon tipped catheter inside an artery found clogged by hard, calcified materials (hard plaque). As the balloon is inflated, plaque is pushed against the inside wall, allowing a bigger opening inside the artery and restoring normal blood flow. Unfortunately, not all types of plaque are good candidates for TAB operation: when unstable plaque (a thin calcified fibrous layer covering a bubble of liquid fatty materials) is treated by TAB, the operation might cause serious complications and lead to re-hospitalization or even death. A system capable of characterizing *in vivo* the local morphological properties of the artery will have the potential to recognize rupture prone (i.e., unstable) plaque and save lives. Up to the present time no simple technique has been proven to effectively diagnose vulnerable plaque in real time and *in vivo*.

The object of this study is to introduce a novel impedance-based technique that can recognize unstable plaque. The proposed system consists of an array of active miniaturized piezoelectric (PZT) sensors surface-mounted on an angioplasty balloon. The balloon is inflated at low pressure to ensure physical contact between the artery and the sensors. The acoustic impedance of the sensors touching the arterial wall are measured and compared to an existing baseline. By studying the variation of impedance, valuable information on the acoustic properties of the probed wall is thus acquired. Since hard, calcified plaque has different acoustic properties from liquid lipids, it is possible, by means of studying impedance variation through the wall thickness, to determine the morphological features of the probed wall.

Paper SHM 2002-162

Structural fault detection and isolation using neural networks based on response-only data

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To diagnose faults in vibrating structures, neural networks were trained with transmissibility data from two different systems. The data were from finite element simulation and vibration experiments. The networks gave very clear diagnosis of the faults in the rigs, which suggest that the transmissibility function is a sensitive source of structural fault information if the measurement points are located properly.

In the present paper the data of the ordinary transmissibility function is used to train neural networks. The advantages of transmissibility functions are apparent; firstly, transmissibility measurement does not involve the measurement of the excitation force, so it is easy to be obtained from structural systems in working state, such as a running turbine generator systems, vehicles on the road, bridges with heavy traffic, airplanes in flight and so on. This advantage allows very practical and wide applications on fault detection. Secondly, the reference and response points for the transmissibility function can be chosen freely so that the most sensitive locations to the faults of important components may be used, which will improve the diagnosis accuracy of the location of the possible faults.

To demonstrate the validity of this approach, one or two typical engineering structures are simulated and the method is applied on the simulation transmissibility data.

The networks are trained with the data and then tested. The results give a clear indication of the occurring of the faults and their locations, which makes one confidently believes that with the transmissibility function data neural networks are able to detect faults in the system which cause changes of its transmissibility function.

Paper SHM 2002-163

Damage Detection of Composite Laminates Using PZT Generated Lamb Waves

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Composite materials are increasingly being used in primary structures because of their superior strength-to-weight and stiffness-to-weight properties over isotropic materials. However, fibre reinforced materials are more complex in nature and analysis. Their macroscopic anisotropy and the fact that they consist of different materials (fibres and matrix) generally results in various types of damage with different propagation characteristics. Low-velocity impact can cause matrix cracking, delaminations and broken fibres leading to significant degradation of stiffness and strength properties. Flaw detection and determination of the remaining strength and life of the structure is a challenging task.

Most of the state-of-the-art non-destructive techniques (e.g. ultrasonic C-Scan, radiography, thermography) for composite materials are not suitable for in-situ health monitoring. They might require removal of individual components for testing, employ bulky transducers, require point scanning and in general be time-consuming and expensive. Non-destructive inspection of structures using Lamb waves is a very attractive technique [1]. Lamb waves are two-dimensional acoustic waves and can be generated in relatively thin solid plates with free boundaries. They can be divided in symmetric and antisymmetric modes according to their displacement pattern. In order to inspect a large panel using Lamb waves a line scan would be employed rather than a point scan which is required in the conventional C-Scan. Hence, greater propagation distances could be achieved and the whole line between the transmitter and receiver could be interrogated, since a through thickness excitation is produced.

In this project small piezoelectric patches have been selected for the generation and reception of low-frequency Lamb waves. Their low weight and volume makes them suitable for incorporation into smart structures. Moreover, they can operate in longitudinal (d_{31}) mode, which gives the flexibility of working at relatively low frequencies and thus significant economic savings can be achieved.

The aim of the present work is to develop a system of smart devices that could be permanently attached to the surface of the structure and monitor the interaction of Lamb waves with defects in composite laminates. Using a linear array of transmitters would generate a relatively uniform wavefront allowing the inspection of large areas with a limited number of sensors, Díaz Valdés and Soutis [2]. The damage inspection strategy is shown in Figure 1. In principle, this method involves the analysis of the transmitted and/or reflected wave after interacting with the test-piece boundaries or

discontinuities. Changes in the response of the acquired signal are induced by the presence of damage and permit the estimation of the criticality and location.

In the present work, the wave propagation characteristics of the antisymmetric Lamb modes in composites are studied. Different theories for the calculation of group and phase velocities of flexural waves are evaluated. The wave propagation in plates and the interaction with delaminations (interlaminar cracking) is also examined. The A_0 antisymmetric Lamb mode is generated in CFRP quasi-isotropic laminates using a linear array of transmitters operating in-phase at low-frequencies. Finite Element analysis is performed in parallel and an attempt to determine the optimum number and positioning of piezotransmitters for a given plate geometry is made. It will be shown that typical-size defects in composites can be successfully identified.

References

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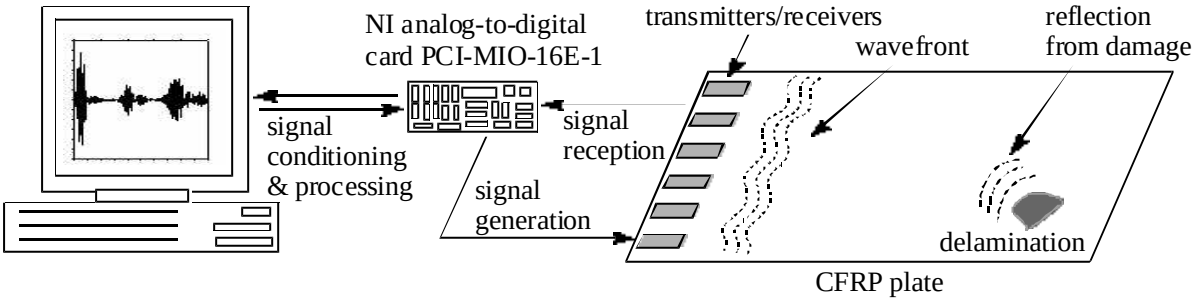

Figure 1 Damage detection configuration.

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Paper SHM 2002-164

Compressive Behaviour of Composite Bonded Patch Repairs

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The proportion of fibre composite materials being used in aerospace, industrial, automotive and marine structures is increasing year on year. Continuously reinforced thermosets are currently the most popular composite systems that are offering higher specific stiffness and strength compared with conventional engineering materials. A number of different resins and reinforcements have been 'qualified' for use in a number of different market areas. These structures are without doubt outperforming their forerunners when structural performance parameters alone are considered. However, the inherently brittle nature of composites makes them susceptible to damage caused by low velocity impact. Consequently, it has been necessary to develop repair methods so those costly components are not scrapped due to in-service damage. Current repair concepts of composites include a wide range of approaches from highly refined and structurally efficient but expensive flush patch repairs to the external mechanically attached metal or composite patch. In all these repair methods the main concerns are the prediction of both strength and durability of the repaired laminate.

In this paper the compressive behaviour of external bonded patch repaired composite laminates is examined. The compressive loading mode is more severe than the tensile mode due to instability of delaminated plies, instability of the patch and skin strength reductions occurring under elevated temperatures and absorbed moisture conditions. A non-linear shear lag stress analysis is performed on a double-lap joint in order to identify critical joint parameters and design an efficient external patch repair. It is found that oversized patches not only increase the structure's weight but also increase the stress concentrations in the repaired region, which can cause premature failure. Reducing the patch thickness near the edges of the overlap and increasing the local adhesive thickness decreases the stress concentration in both shear and peel stresses. A three dimensional finite element analysis is then performed to determine the stresses in the optimum repaired configuration and used with a fracture failure criterion to predict the ultimate failure load. Experimental measurements show that carefully designed bonded patch repairs can recover almost 80% of the undamaged laminate strength. In near future research work PZT transmitters will be attached to the repaired structure in order to monitor in-service damage development in the form of matrix cracking and delamination.

Paper SHM 2002-165

Structural Damage Detection Using The Combination of ICA and ANN Techniques

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This paper presents a novel approach to structural damage identification based on combining independent component analysis extraction of time domain data and artificial neural networks. The advantage of using time history measurement from sensors for damage identification is that it provides the original vibration information. However, the volume of data, measurement noises, and lack of reliable feature extraction tools are the major obstacles. To circumvent them, the independent component analysis technique is applied to represent the 'measured' data with a linear combination of dominant statistical independent components and the mixing matrix A. Such a representation seems to capture the essential structure of the measured vibration data. The vibration features represented by mixing matrix provided the relation between the measured vibration response and the independent components and were then employed to build the simplified neural network model for damage identification. A further advantage of this particular approach was found to be the ability not only to deal with the relative high measurement noises and the data reduction, but also to provide the higher order statistics that could be much helpful for damage identification.

A truss structure, with the time displacement data being simulated, was applied to investigate the method. The 630 set of time wave specimen were simulated to depict one healthy state and nine damage states at different truss elements, with added noises up to 30%. After ICA feature extraction, 540 of them were used for network training and verification and 90 of the rest for network testing. The results showed that it was possible to classify the healthy and damage states happened in various elements with very good accuracy and repeatability.

Paper SHM 2002-166

Multi-channel FBG sensor system for static and dynamic measurement up to 10 kHz

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Sensors for strain measurement are indispensable for structure monitoring. Fiber optic sensors based on Fiber Bragg Grating (FBG) technology are found to be suitable for strain sensing and has a number of advantages compared to conventional strain gauges. TNO has developed an interrogation/demultiplexing system for FBG sensor array. This system is based on a special designed spectrometer. The main features of the TNO system are the combination of absolute measurement with a high readout frequency, the multi-line configuration and a simple design without moving parts. The combination of absolute measurement with a high readout frequency is of importance for the detection of dynamic loading because the effects and consequences of dynamic loading depends strongly on the static load level. A demonstrator of the TNO system is designed and built with COTS components. The demonstrator is designed for 32 FBG channels. A sampling frequency of about 19 kHz simultaneously for all FBG channels is achieved. Several experiments are carried out and shock wave propagation in a plastic rod is demonstrated.

Paper SHM 2002-167

Strengthening and repair of a monument in Cairo

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The dramatic effect of the environmental attack on our architectural heritage in old Cairo have urged the civil engineers to extend their activities and employ their scientific and technological knowledge to restore those unique valuable monuments.

This paper presents a study carried out to strengthen and repair one of the most significant and rare mosques in Cairo. It was built in the Fatimids epoch. The mosque was deteriorated both structurally and architecturally. Most critical problem was due to differential settlement of the foundation elements as a result of severe environmental changes. The structure was built of limestone, and the foundations were an enlarged extension of the limestone walls below the ground level. The ground water table has risen dramatically till it reached the ground surface in some parts of the mosque. Moreover, the ground trenches and piezometers installed at the site showed that running water is penetrating the soil. This water is loaded with chemicals, salts, and organic matters. It is a leakage from deteriorated sewers that served the crowded old district for more than half a century.

The site investigation indicated that the mosque was founded on thick layer of heterogeneous fill followed by sand inter-layered by silty clay. The soil profile contained cavities under the building. It was realized from historical records that the mosque was built on the ruins of a palace that is now buried beneath the foundation level. This phenomenon was examined by geophysical methods such as electrical resistivity and seismic surveys. Both techniques proved the existence of cavities in different areas of the site. This finding ruled out the possibility of using grout injection to reinforce the bearing strata.

Structural cracks caused by differential settlement were monitored for a period of time to record the movement of the building. The problem called for the cooperation of the structural engineer who studied the statistical system of the masonry old building and analyzed the loads transferred through arches, columns, and walls to the foundation soil.

The structural analysis, monitoring of the building and the site investigation led to a certain engineering solution to restore the mosque. The rehabilitation scheme included the execution of micro-piles to strengthen the foundations. The bearing soil, and to redistribute the loads on the soil layers.

The rehabilitation scheme put together by the geotechnical, structural, and architectural engineers was quite successful for restoring this valuable historical monument, and set a guide for saving other monuments in old Cairo.

Paper SHM 2002-168

Water Network Diagnostics

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A software tool for signal processing in health monitoring of water networks is presented. It is assumed that the water pressure in the network's nodes in a distance of inspected area can be measured and also that a diameter of some selected branch of the network can be modified in a controlled way. Then, making use of the analytical network model of this installation and using presented in the paper, so called Virtual Distortion Method (VDM), the water leakage can be detected and identified (single as well as multiple locations and their intensities). The proposed identification methodology takes advantage of gradient based optimisation technique.

The problem of detection and identification of leakages (mostly due to corrosion) in water networks is an important issue. The problem of management of water sources is more and more important in the world scale. On the other hand, the consequences of unpredicted failure in the operating water network can be very grave. Therefore, there is requirement for an automatic monitoring system able to detect and localize leakages in the early stage of their development. The proposed approach is based on continuous observation of the pressure distribution in nodes of the water network. Having a reliable (verified versus field tests) numerical model of the network and its responses for determined inlets and outlet conditions, any modifications to the normal network response (pressure distribution) can be detected. Then, applying proposed in the paper numerical procedure, the inverse problem of the water flow distribution can be performed. The possibility of simultaneous detection of several leakages with different locations and intensities is included into the proposed methodology.

The proposed methodology for the failure identification is based on so called Virtual Distortion Method (VDM) approach, applicable also in the problem of damage identification through monitoring of piezo-generated elastic wave propagation (Ref.1). This technique (called Piezodiagnostics) is focused on efficient numerical performance of I inverse, non-linear, dynamic analysis. The crucial point of the concept is pre-computing of dynamic structural responses for locally generated impulse loadings by unit virtual distortions (similar to local heat impulses). These responses stored in so called influence matrix allows composing of all possible linear combinations of local non-linearities (due to defect) influence on final structural response. Then, using a gradient based optimisation technique, the intensities of unknown, distributed virtual distortions (modelling local defects) can be tuned to minimize the distance between the computed final structural response and the measured one.

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Opto-mechanical behavior of optical fibers for structural monitoring. Part 2 : Experimental verification

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The present paper follows the same title Part 1, [1] to analyze the signal transmission in fiber optics, undergoing stress and strain conditions. The objective is to use the fiber optics as facility built-in sensors, for both structural monitoring and research. In the Part 1 theoretical aspects related to power loss (attenuation) phenomena of transmitted optic signal have been modeled for applications characterized by small values of length and radius curvature.

In this paper the experimental verification is reported; a test bench has been designed, which allows the geometrical configuration of fibers to be defined and checked, to be able to measure the attenuation values corresponding to known stress and strain conditions.

The study activities was concluded with a satisfactory review of theoretical forecasts, provided that the numerical model is properly implemented. The possibility of carrying out structural monitoring on textile composite materials has also been investigated, and has shown the effectiveness of the measuring setup.

Paper SHM 2002-170

Monitoring of temporary cables in “Infante D. Henrique” bridge

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A new arch bridge under construction in Portugal is presented. The extreme shallowness and flexibility of the arch implies great complexity of construction and requires a very complete control of geometry, deformations and forces. The paper describes the main features of the implemented monitoring systems, discussing the control of the cable forces.

Paper SHM 2002-171

A New Concept for Structural Health Monitoring Applied to Composite Material. Part 1: Theoretical considerations

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A model of electromagnetic behavior of composite materials like carbon epoxy or glass epoxy structures has been developed. Based on this model, an electromagnetic method allowing to evaluate the electric conductivity and the electric polarization of this type of material by measurement of magnetic and electric components of an incident electromagnetic wave crossing through the material has been also developed. A local measurement of magnetic and electric field allows to detect the presence and the extent of a damage if it induces a local variation of electric conductivity and/or electric polarization. This method present a great sensitivity to detect damages inducing local variations of electric characteristics such as burning and liquid ingress. However, the sensitivity towards mechanical damages such as delaminations is clearly smaller, contrary to acousto-ultrasonic methods.

Based on the complementarity of the two techniques, electromagnetic and acousto-ultrasonic, a new concept is proposed, combining them in an unique Structural Heath Monitoring System (SHMS). The new SHMS, which consists of a network of electromagnetic and ceramic piezo-electric sensors, and the main results performed with this dual method applied to a carbon epoxy structure including various defects (impact delaminations, local burning and liquid ingress) are presented and discussed in a companion paper [1].

Here, theoretical considerations are given concerning the electromagnetic behavior of composite structures made of carbon epoxy laminates and glass epoxy materials, and the various possible electromagnetic techniques are presented.