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WIESŁAW OSTACHOWICZ[1]

Identification of damage location in structures

This paper is a personal perspective of structural health monitoring technology and its applications as seen from a current literature and projects. Recently, laminated composites with built-in piezoelectrics have attracted significant attention among researchers because of their potential application to controlling vibrations, suppressing noise, as well as monitoring the health of the structures. The investigated damage detection system is based on the known fact that material discontinuities affect the propagation of elastic wave in solids. The change in material characteristics, such as a local change in stiffness or inertia caused by a crack or material damage, will affect the propagation of elastic waves and will modify the obtained signals. Wave frequencies associated with the highest detection sensitivity depend, among others, on the type of the structure, the type of material, and the type of the damage. The paper is not intended to be a comprehensive survey but merely to present a flavour of recent activity in this important subject.

1. Introduction

Early detection of problems such as cracks, delaminations, loss of bond, and corrosion losses can prevent a catastrophic failure or structural deterioration beyond repair. Maintenance methods can be roughly divided into reactive, preventive, and predictive. Reactive, or breakdown, maintenance is implemented only after a given structure or its element fails. The savings related to its low set-up and operating costs are usually quickly wiped out by high costs of unscheduled outages (e.g., the cost of organising and maintaining a bridge detour), and expensive repairs associated with unexpected failures.

Preventive maintenance programs are usually designed around maintenance management software. The software schedules periodic maintenance and analyses the related cost. This type of maintenance is currently widely used and has been shown to reduce costs as much as by 30%, when compared to reactive maintenance (Zwingelstein, 1996). However, the preventive maintenance approach also results in many unnecessary maintenance procedures. This not only increases the labour cost, but also causes unneeded outages, and may even create new problems

[1]Institute of Fluid-Flow Machinery PASci, Centre for Mechanics of Machines, Fiszera 14, 80-952 Gdańsk, Poland

due to, e.g., faulty re-assembly.

These disadvantages led to the development of predictive maintenance concept. This method is based on the assessment of the actual condition of a given structure or machine through the monitoring of signals that can be associated with damage in a particular piece of equipment. There are several advantages of this approach: the condition of a given structure or machine is known at any moment, maintenance can be scheduled to reduce the cost of downtime, and the possibility of a breakdown is very significantly reduced. The predictive maintenance method has been shown to reduce maintenance costs by 2% to 10%, when compared with the preventive maintenance approach. An effective implementation of the predictive maintenance approach requires the application of an adequate monitoring system. Such a system should be reliable, cost-effective, rugged, and easy to maintain.

The damage identification problem has two characteristics that make it difficult to solve. First, it is an inverse problem. Compared with a direct dynamics problem whose goal is to find the system response for the given system model, the damage identification problem tries to find the damage magnitude for a given system response. Second, it is nonlinear problem. Several numerical and analytical techniques have been proposed or adopted for the technical applications. Modal analyses, system identification, neural network algorithms, genetic algorithms, optimisation algorithms, etc., have shown some promising results.

2. Current status

This section describes efforts done in the area of real-time NDT systems based on smart materials. The goal of these efforts is to develop reliable and inexpensive systems integrated with monitored structures, capable of real-time condition assessment.

2.1. Structural monitoring systems currently under development

Several of NDT methods currently being developed may satisfy these requirements. The most promising approaches are based on detecting: (1) Acoustic Emissions (AE), (2) strain variations in optical fiber sensors, and (3) anomalies in elastic waves propagation. The implementation of each of these techniques consists of two major elements: (1) a sensor system, and (2) a data processing system. Brief descriptions of most frequently used sensing and data processing systems follow.

2.2. Sensing techniques

The Acoustic Emissions method is based on the detection of stress waves generated by cracking material (Holford and Carter, 1999). Ohtsu (1996) and Ikegami

(1999) give overviews of AE method applications in Civil and Aeronautical Engineering, respectively. Goranson (1997) described attempts by Boeing to apply AE methods to monitor vital elements of passenger jet structures. Due to problems with separating signals generated by cracking material from ambient noise, and difficulties in localizing AE sources this project was eventually abandoned. However, recent studies related to military applications indicate a limited success for simple structures (Kudva, et al. 1999).

Optical fiber sensor systems are based on detecting variations in the parameters of light passing through optical fibers embedded or surface-bonded to a structure. Applications of fiber optic sensors to monitor Civil and Aeronautical Engineering structures have been described by Mita (1999), Todd et al. (1999), Foote (1999) and Sirkis et al. (1999). Optical fiber sensors do have many advantages: they are low weight, immune to electromagnetic interference and nonconductive. But, this type of a sensor also has several serious disadvantages. They are difficult to apply to steel structures, because they would not survive high temperatures during welding (Kiremidjian, et al. 1997). The effect of an alkaline environment in concrete on fiber coatings has not been fully understood (Ansari, 1997). Also, this type of a sensor can not be embedded in an existing structure, and surface-bonded fibers will not sense most of internal damages.

The third type of currently investigated damage detection systems is based on analyzing anomalies in elastic wave propagation through the monitored part. Elastic waves are generated and sensed by an array of transducers embedded or surface-bonded to the structure. Signals transmitted among the elements of the transducer array are processed by some type of algorithm associating detected anomalies with damage size and location (Choi and Chang, 1996; Lin, 1999; Biemans et al., 1999). This approach is similar to the classical ultrasonic testing, except that wave frequencies are usually much lower, sensors/transmitters are fixed to the monitored structure, and collected data are automatically processed. Varadan and Varadan (1999), Pines (1998) and Kiremidjian (1997) presented solutions for wireless signal and power transmission. Shen et al. (1996) outlined a method of monitoring manufacturing quality and damage characteristics in composite structures using piezogenerated elastic waves.

Although applications of Acoustic Emissions and fiberoptics are promising, the research based on analyzing anomalies in piezo-generated elastic wave propagation is focused on developing a damage detection system. The reasons are the following: (a) correctly designed piezotransducers can send various types of signals, e.g., flexural, compressive, and shear waves, (b) piezotransducers can autofocus on damage, (c) appropriately distributed arrays of piezotransducers can assess the condition of the entire volume of critical structural elements.

2.3. Data processing systems

The majority of data processing systems are based either on statistical principles (Castanien and Liang, 1996; Vanik and Beck, 1997) or on the application of "soft computing" neural networks, genetic algorithms and fuzzy logic (Liu et al., 1999; Mares et al. 1999). Luo and Hanagud (1997) demonstrated the application of fuzzy logic to improve the performance of a neural network used for structural health monitoring. Numerous industrial applications of neural networks in machine condition monitoring are outlined by Tsoukalas and Uhrig (1997). Soft computing methods appear to be extremely useful in damage detection systems, since they are able to correctly process noisy data and adapt to the changing environment. Neural networks and fuzzy logic approaches have reached maturity and have been successfully applied to detect vibration response anomalies associated with structural damage (Kirkham et al., 1999).

3. Anomalies in elastic wave propagation

In recent years, investigations have been based on analysing anomalies in elastic wave propagation through the monitored part. The investigated damage detection system is based on the known fact that material discontinuities affect the propagation of elastic waves in solids. Wave frequencies associated with the highest detection sensitivity depend, among others, on the type of the structure, the type of material, and the type of the damage. Elastic waves are generated and sensed by an array of transducers embedded or surface-bonded to the structure. Piezoceramic material has been selected as the primary candidate for transducer construction. Piezomaterials convert electrical energy to mechanical strain and thus are capable of producing an elastic wave propagating through the structure. A very wide frequency spectrum can be generated. Piezotransducers can auto-focus on damage and have the capability of producing various types of waves, e.g., flexural, compressive or shear waves, using the same set of piezoelements.

Figure 1 is a schematic drawing of a conceptual damage identification system that can estimate the location and time history of a damage using the measured signals from the sensors built into the structure. The considered system is denoted as 1, 2 denote damage, and 3 represents a pair of piezoelectric transducers. The plate is instrumented with four pairs of piezoelements (1, 5, 6, 8) bonded to both faces of the plate. Each of these pairs can be used as a transmitter or as a receiver. Local actuators dynamically excite the structure while sensors measure its response. Assume that the piezotransducer 1 generates elastic waves with a profile appropriate for a given task (burst chirp, harmonic signal, etc.). This signal will be picked up by piezotransducers 5, 6, and 8. After recording signals received by transducers 5, 6, and 8, the transducer 5 will become a sender, and signals received by transducers 6, 8, and 1 will be recorded. A processor compares the response to a baseline measured earlier from the undamaged structure. If the responses differ, then the structure may be damaged.

This procedure is repeated until a set of twelve transfer functions, with three functions generated by each of the piezotransducers, is recorded. Any change in the structure's characteristics, such as a local change in stiffness or inertia or a change in mechanical admittance caused by a material defect, will create anomalies in propagated elastic waves and modify the received signals. These anomalies

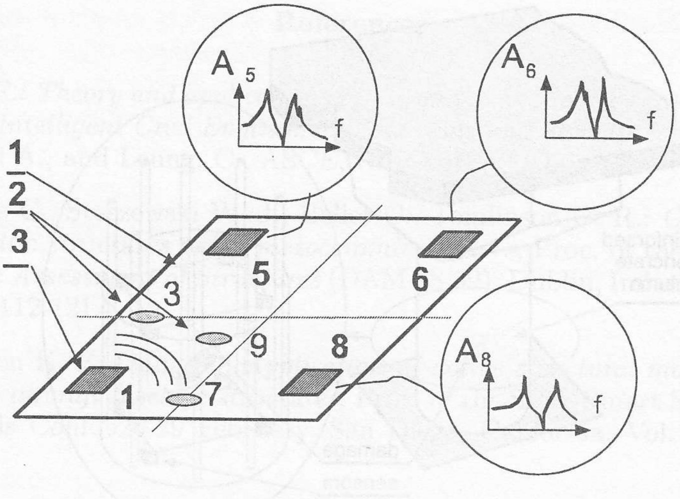

Fig. 1. A schematic drawing of damage identification concept (Kawiecki et al.).

are analysed and interpreted by a "soft-computing" – based system, which uses this information to estimate the location and size of the defect. The same concept can be extended to three dimensions and used to monitor the condition of, e.g., a typical civil engineering structure (see Fig. 2).

The main objective of the theoretical portion of this problem is to develop a model allowing to determine the relationship among the power of a transducer, the frequency of generated signal, the type of monitored solid and the range of effective signal transmission. The frequencies used in this technique are much higher than those typically used in modal analysis based methods but lower than in ultrasonic testing. At such high frequencies, the response is dominated by the local mode and the wavelength of the excitation is small enough to detect incipient-type of damage. Ultrasound is highly effective at both finding damage and determining its severity. However, it requires specialised inspection facilities usually only available at manufacturer's plant. Ultrasound is difficult to use for structures that cannot be disassembled or that are remote from any inspection facility.

With the selection of the diagnostic waves, the waves reflected from the boundary could be clearly detected, and, as a consequence, the possibility of the sensor signals being corrupted by the reflected waves could be minimised.

The diagnostic methods consists of a structural model and a response comparator. The structural model calculates the sensor measurements for a given magnitude and location of defect. The comparator compares the sensor measurements with the simulations generated from the structural model to estimate the magnitude and location of defect. The code, which serves as the controller, can be directly linked with distributed sensor measurements for identifying both location and magnitude of defect.

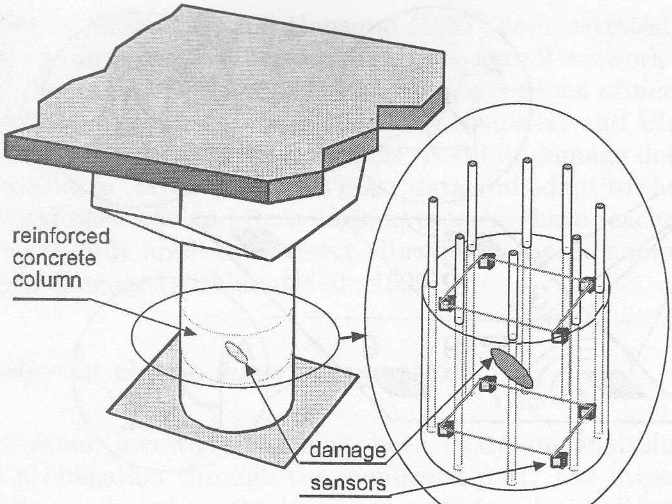

Fig. 2. A concept of damage identification in highway overpass column (Kawiecki et al.).

The accuracy and reliability of the system strongly rely upon the accuracy and reliability of the analysis for relating the sensor measurements to the physical changes in the structures. Sensor measurements are point-wise in the continuous structures. Damage or abnormal condition may not appear at the location where the sensor is located. Therefore, sensor information needs to be extrapolated for prediction of damage that appears at a distance away from the sensor location.

4. Concluding remarks

Identification of damage location based on analysing anomalies in elastic wave propagation is a new, promising technology that has attracted significant attention in recent years for its potential wide applications ranging from civil infrastructures, land and marine vehicles, and aircraft to aerospace transportation vehicles. The development of the technology involves multi-disciplinary field including sensors, signal processing, system integration, signal interpretation, etc.

Successful development and implementation of the technology could lead to reduction in costs associated with maintenance, minimisation of downtime avoiding unnecessary economic loss, and improvement of the safe use of structures.

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