Recent Trends in Structural Health Monitoring Technologies

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INTRODUCTION

The subject of structural health monitoring (SHM) is emerging as an increasingly important component of overall Nondestructive Evaluation (NDE) programs and is now being considered for implementation in a variety of applications including spacecraft components, bridges, and aircraft. Over the past several years, there have been a number of limited demonstrations of SHM in actual field applications. In addition to the Army, Navy and Air Force, other federal agencies interested in this topic include the Federal Aviation Administration, NASA and the Department of Transportation. The detection of damage at any location is a common challenge in most large structures, and thus SHM has potential applications across a range of industrial sectors. Examples include the detection of impact induced delaminations in composite aerospace structures, localized corrosion in petrochemical plants and unauthorized penetrations of shipping containers.

Successful field implementation of SHM has not been widely achieved and depends on overcoming several roadblocks including the development and demonstration of SHM sensors that have long term stability and reliability, validation of the capability of the SHM systems in terms of the probability of detection of flaws, and finally the integration of the SHM system results into structural and platform maintenance strategies. An increasing number of efforts are focusing on identifying these implementation issues and developing solutions for them. The Army, Navy and Air Force recently sponsored a workshop to address these issues.[1] The benefits that will flow from successful implementation of SHM will include: replacing schedule-based inspection/maintenance of a structure by condition-based maintenance; significantly reducing life-cycle cost, and improving safety of new as well as aging aircraft, aerospace, and civil structures.

Defining Structural Health Monitoring

SHM has been defined differently by various research groups. For instance, it has been defined as a system with the ability to detect and interpret adverse "changes" in a structure in order to improve reliability and reduce life cycle costs.[2, 3] The greatest challenge in designing a SHM system is knowing what "changes" to look for and how to identify them. The characteristics of damage in a particular structure play a key role in defining the architecture of the SHM system. The resulting "changes," or damage signature, will dictate the type of sensors that are required, which in turn determines the requirements for the rest of the components in the system. Much current research focuses on the relationship between various sensors and their ability to detect "change" in a structure's behavior. Another author defines SHM as the "continuous, autonomous in-service monitoring of the physical condition of a structure by means of embedded or attached sensors with minimum manual intervention, to monitor the structural integrity of the structure."[4] SHM includes all monitoring aspects related to damages, loads, conditions, etc., which have a direct influence on the structure. The sources of faults can result from fatigue, corrosion, impacts, excessive loads, unforeseen conditions, etc. Regardless of the definition, however, all SHM systems require a combination of data acquisition by sensors and adequate computational models of the structure.

For aircraft applications, the uses of SHM technologies for future aircraft will not only enable new possibilities for maintenance concepts but will have a significant influence on design concepts and assembling technologies. SHM is expected to be one of the key technologies for controlling the structural integrity of future aircraft, providing both maintenance and weight saving benefits. Some of the advantages over conventional NDE inspection include reduced inspection down time, elimination of component tear down, and potential prevention of failure during operation. SHM is likely to be used in identifying failures in aircraft, which would also be a boon to the commercial aircraft industry.

EMERGING SHM TECHNOLOGIES

The foundation of structural health monitoring is the ability to monitor structures using embedded or attached nondestructive evaluation sensors and to utilize the data to assess the state of the structure. Over the last ten years researchers have made significant advances in developing NDE sensors for SHM, and they have developed the hardware and software needed for analysis and communication of the SHM results.

The NDE SHM sensors that have reached some modest degree of maturing and are able to monitor significantly large areas of structures include fiber optics, active ultrasonics, and passive acoustic emission. Eddy current type sensor arrays have also been shown to be potentially useful in monitoring local areas in electrically conducting materials.

Fiber Optic Sensors

A 2001 study reviewed the early development of fiber Bragg grating (FBG) based NDE sensors and also provided an explanation of the complex physical principals underlying these sensors.[5] Fiber optic sensors generally utilize a laser light source to transmit light through the fiber, which is either bonded to the surface of a structure or embedded in a structure. The perturbations to the laser light involving phase, amplitude, and frequency are a function of the temperature and stress of the fiber optic, which are in

Figure 1. Schematic of HOPE-X.[9] (Provided courtesy of Japan Aerospace Exploration Agency (JAXA))

turn a function of the state of the structure. Over the past several years, FBG sensors have been the subject of very active R&D and commercial products are now appearing on the market. FBG sensors are particularly suited to fiber reinforced polymer composite structures since the small fiber optics can be placed in the composite during its manufacture.

Japanese researchers have been particularly active in developing fiber optic sensors systems for SHM.[6-9] Perhaps the most interesting work involved the study of the application of both surface mounted and embedded fiber optic distributed sensors to full-scale monitoring of large composite structures.[9] The authors monitored strain or temperature during composite manufacture and stiffness for in-service structural performance. The carbon fiber reinforced plastic composite structures studied were International America's Cup Class (IACC) yachts and a Japanese experimental reentry space vehicle (HOPE-X). In both cases, fiber optic sensors were used to measure strain and temperature. The authors concluded that they could measure strain and temperature in these full-scale composite structures, and their work demonstrated the great potential of fiber optic distributed sensors for SHM of large structures. Figure 1 shows the fuselage of the reentry vehicle that was monitored for temperature and strain during the cure cycle and also for strain in subsequent structural testing.

Passive Acoustic Emission Sensors

Acoustic emission sensors are utilized to detect and monitor the ultrasonic waves produced by materials when materials undergo cracking that can lead to structure failure. By means of triangulation, an array of acoustic emission sensors attached to a structure can be used to determine the location of growing cracks in a structure. In addition, highly sensitive fiber optic Bragg sensors, either attached to the surface or embedded in a structure, can be used to detect acoustic emission signals.

As an example of the broad research and development of acoustic emission sensors for SHM, a new class of continuously active fiber composite sensors was developed to detect damage in composite materials.[10] Active fiber composite (AFC) materials were a new class of materials developed at MIT in the late 1990s and further developed at NASA as microfiber composites (MFC) for use in actuator applications. AFC materials were reconfigured and fabricated to make low cost sensors that can detect strain levels as well as acoustic emission signals. This resulted in a tremendous reduction in the number of data acquisition channels needed for SHM of large structures, and it greatly increases the chance of having acoustic emission sensors near an acoustic emission source. Since ultrasonic waves generated by acoustic emission events attenuate rapidly, it is essential to have a sufficient distribution of sensors in composite structures. The response of AFC sensors (also known as piezoceramic active fiber sensors) was modeled, and the researchers described how to manufacture these sensors. Figure 2 shows the design of a 2x2 sensor array used by the researchers.

The authors concluded that AFC sensors were able to detect actual damage propagation in a composite structure tested to failure long before the structure failed. When compared to conventional acoustic emission sensors or piezoelectric patch transducers, the AFC sensors also showed increased ruggedness and greatly improved unidirectional sensing and higher efficiency.

Active Ultrasonic Sensors

Research on active ultrasonic sensors for SHM has received a great deal of attention over the last several years with researchers from several countries, including the United States, the United Kingdom, France, Germany, and China, contributing to the literature. Many of the research efforts have focused on the use of ultrasonic Lamb waves for SHM or the use of electromechanical impedance methods using piezoelectric wave active sensors. As an example, the optimization of piezoelectric ultrasonic patch sensors for the Lamb wave monitoring of composites was studied.[11] The researchers studied the optimization materials and configurations for this type of sensor and carried out theoretical and experimental studies to determine and demonstrate the capability of these sensors. The authors of this research stated that they were able to greatly improve the performance of this class of sensors, and they believed that their further development of new wavelet analysis techniques have also enhanced sensor capability. It was concluded that Lamb waves provide a very good technique for SHM of composites, and they will be used in future field applications.

As another example, researchers investigated monitoring the changes in the electrical impedance of piezoelectric transducers

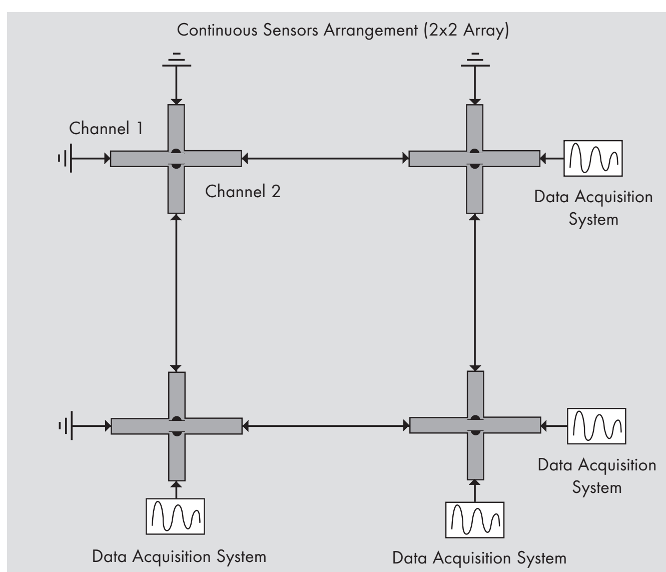

Figure 2. Design of a 2 x 2 array of continuous sensors with two channel AFC sensor nodes.[10]

as a function of damage in structures.[12] Physical changes in the structure cause changes in the mechanical impedance of the structure, and this is detected by changes in the electro-mechnical coupling of the piezoelectric patch transducers either bonded to the surface or embedded in the structure. Figure 3 shows the interaction between a piezoelectric transducer and its host structure as described in a simple one-dimensional model.

The research concluded that the effectiveness of sensors for SHM using changes in the electrical impedance of piezoelectric transducers was successfully demonstrated.

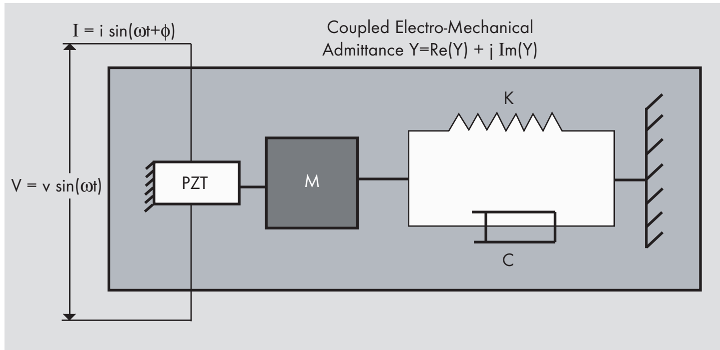

Figure 3. **1-D model used to represent a lead-zirconate-titanate (PZT)-driven dynamic structural monitoring system.[12]**

SELECTED SHM EXAMPLES

In this section, selected examples of applications of SHM to a variety of structural systems are provided, including aircraft and aerospace systems, space vehicles, offshore structures, and railroad systems.

Several interesting examples of SHM applications have been reported recently.[13] These applications are based on significant advances which have been made in recent years to evolve sensor technology from conventional electrical strain gages to fiber optic strain sensors. The technology, especially that associated with optical Fiber Bragg Gratings (FBG), has rapidly matured with an increasing commercial supplier base; the size, weight, and cost of the equipment has fallen dramatically. For interrogating multiple FBG sensors on a single fiber, a time-division-multiplexing (TDM) interrogator unit has been developed that uses a unique optoelectronic architecture capable of high resolution over a wide operating range; it can interrogate over 100 gages, each to their full range, on a single fiber.

In an aircraft application, a number of FBGs on a single optical fiber were embedded in both the web and flange of the forward spar of a developmental composite winglet for a large civil transport aircraft.[13] Using the TDM interrogation system, the FBGs were successful in measuring the strain in the spar, including the shock loads induced by both lightning and bird strike tests. The ability to detect strain during the lightning strike demonstrated the system's resistance to the effects of high voltage electrical pulses.

Another SHM example involves application to offshore oil drilling operations.[13] In deep water operations, tidal currents can cause vortex induced vibrations in the riser pipes that bring the oil and gas from the sea bed to the surface. These vibrations induce strains in the pipe, which can result in premature fatigue failure. The requirement was to measure the strain induced in a 6-inch diameter steel riser pipe and to use the resultant data to help predict the residual life remaining in the riser. To achieve this result, an optical fiber was embedded in a composite half section tube that could then be strapped to the pipe in such a way as to follow the shape of the pipe as it flexed. The optical fiber was placed so that the FBGs were positioned along both edges and the center line of the half pipe. The resulting system was able to detect strains down to one microstrain in the riser pipe. The TDM interrogator was mounted in a container fitted to the half pipe, with data being transferred to the surface using an electrical umbilical. The system has been successfully deployed at depths of 6000 feet on an oil platform in the Gulf of Mexico, and it has been in operation for many months.

The use of ultrasonic transducers to monitor railroad wheels for cracks has also been investigated.[14] The ultrasonic signal is introduced by the high speed contact of the steel railroad wheel to the steel track, and the signal is detected by a PZT transducer placed inside the hollow shaft of the wheel axle. The transducer is configured to withstand the centrifugal forces generated by the rapidly turning wheel and shaft. The transducer is coupled to a wireless transmitter system that sends data to an industrial computer. After development, the SHM system was checked on a railroad test bed run by a German railroad. The system is capable of operating at high wheel speeds, and it reproducibly detects cracks in the wheels.

To meet the concerns of the integrity of NASA's Space Shuttle thermal protection system, a certified SHM system for monitoring impacts to the Reinforced Carbon-Carbon (RCC) on the Shuttle's wing leading edge was developed.[15] In addition, a large effort was described that focused on understanding the damage that took place on Space Shuttle Columbia's leading edge, including a number of NDE techniques that were used to assess the integrity of the Shuttle's leading edge while they were installed between flights.

The conventional NDE techniques investigated to inspect the RCC on the ground included: advanced digital radiography, high resolution computed tomography, thermography, ultrasound, acoustic emission, and eddy current systems. Eddy current array scanning and thermography demonstrated the maturity and capability to inspect the RCC from one side while installed on the Shuttle, and this was successfully field tested at Kennedy Space Center (KSC).

The development of a first generation impact sensing system for the Shuttle wing RCC leading edge was also reported. This system is capable of detecting impacts from foam, ice, and ablator materials during ascent velocities. It is also capable of detecting simulated hypervelocity micrometeoroid and orbital debris impacts during flight. The SHM system was based on wireless accelerometer sensors that had previously been qualified for use on the Shuttle for other applications. This accelerometer based SHM system is now used on all Space Shuttle flights to help ensure the continued integrity of the Shuttle wing's leading edge RCC system. [16]

CONCLUSIONS AND PROGNOSIS

Over the past decade there has been an impressive research and development contribution to the knowledge base required for structural health monitoring to assume its place in the modern paradigm of nondestructive evaluation. This modern NDE paradigm views NDE as a contributor to the successful, full life cycle of materials, components and systems. In this vision, NDE contributes to product and process design, in-line manufacturing process control, after manufacturing inspection, in-service inspection, and structural health monitoring. A slightly more expansive view of the NDE paradigm would broaden the name of structural health monitoring to include also functional health monitoring (S&FHM), since many critical components and systems have more than just a mechanical structural requirement.

The SHM research and development base has now reached a modest level of maturity with a foundation in fiber optic sensors, active ultrasonic sensors for guided Lamb waves and active mechanical impedance measurements, acoustic emission sensors, and wireless communications between sensors and a central station. In order for SHM to take its full place in the modern NDE paradigm and fully contribute to the modern NDE paradigm, several steps need to be taken. These steps include:

- Additional study of the long term stability of NDE sensors embedded or attached to structures, including environmental effects (e.g., temperature) on the sensors;
- Development of quantitative information in the form of POD-type studies on the capability of various SHM systems in a variety of applications, including the need for viable calibration standards and techniques;
- Broader scale application demonstrations on important structures in a realistic field environment over a reasonable period of time and covering a variety of NDE sensors/SHM systems with integration of results into structural/platform maintenance strategies;
- Development and promulgation of standards covering the standard practices needed for the widespread application of SHM.

To accelerate the maturation of SHM, perhaps these steps do not have to be made in sequence since taking some of these steps in parallel could lead to a faster, successful conclusion. Moving SHM R&D into useful application will require a commitment on the part of both SHM technology developers and potential users of the technology. The cost to realize full scale, useful application will most likely be substantial when compared to the costs associated with the R&D that has already taken place, since the cost "snowballing" as R&D is moved along the path to full use is often the case rather than a rarity.

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Erratum for *AMMTIAC Quarterly*, Vol. 3, No. 3, *Commercial Manufacturer Benefits from DoD Technology Transfer*. Superfinishing was not developed by the Army, but rather the process, which was developed in the private sector, was applied by the Army to improve the surface finish and fatigue life of components in helicopter transmissions.

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