Acoustic techniques for structural health monitoring

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Abstract

Future safety and maintenance strategies for industrial components and vehicles are based on combinations of monitoring systems, which are permanently attached to or embedded in the structure, and periodic inspections. The latter belong to conventional nondestructive evaluation (NDE) and can be enhanced or partly replaced by structural health monitoring systems. However, the main benefit of this technology in the far future will consist in systems can be designed differently based on an improved safety philosophy that includes continuous monitoring. This approach will increase the efficiency of inspection procedures and reduce inspection time. The Dresden branch of Fraunhofer IZFP has developed network nodes, miniaturized transmitters and receiver systems for active and passive acoustic techniques and sensor systems that can be attached to or embedded in components or structures. These systems have been used to demonstrate intelligent sensor networks for monitoring of aerospace structures, railway systems, wind energy generators, pipes and others. Defects have been detected and monitored during full scale fatigue tests. This paper will discuss opportunities and future trends in nondestructive evaluation and health monitoring based on new sensor principles and advanced microelectronics. It will outline various application examples of monitoring systems based on acoustic techniques and will denote further needs for research and development.

1. Initial Situation

The most dominant goal of technical developments is the improvement of reliability particularly with respect to human safety and security. During the last 20 years, human safety and security issues were the driving force behind technical research and development. The German language combines the English terms of safety and security in one word “Sicherheit”. For technical installations, “Sicherheit” in terms of security includes the
protection from criminal and terrorist assaults, i.e. the deliberate abuse of operating equipment. “Sicherheit”, in terms of safety, is related to avoiding damages caused by the failure of installations and/or means of transportation, including failures from inadvertent operating and human errors.

The failure of technical installations is predominantly caused by:

- Non-conforming operation
- Overload conditions
- External, unfavorable circumstances
- Material or design flaws
- Change of design-critical material characteristics caused by ageing processes and/or corrosion

Technical materials and components are usually designed to operate close to full capacity primarily achieve cost and energy efficiency requirements. Nevertheless, safety margins are applied during the design phase and safety relevant components are subjected to regular in-service inspections and, if required, replacement thus giving rise to significant expenditures for the operation of technical installations and all types of vehicles.

Condition monitoring in the power generation industry is related to the periodical nondestructive testing of systems and components and is referred to as in-service inspections. However, current trends are moving towards the continuous monitoring and surveillance of load and stress conditions of materials, systems and components during operation. This approach requires the integration of sensors into parts and components and the installation of sensor networks to establish and maintain communications with the monitoring system. This system is called Structural Health Monitoring and is referred to as SHM in German technical terminology.

The advantages of this new technique are significant and allow controlled systems and installations to exceed normal requirements for safety, reliability and usage availability.

These techniques can be applied during the early design and development stages and can be verified and validated during accelerated structural tests and result in:

- Extended service cycles with reduced maintenance duration
- Replacement of scheduled periodical maintenance by condition based maintenance
- Monitored systems exhibit a longer operating life and permit full use of the material life
- Monitored vehicles attain a higher resale value and thus represent a direct advantage for the operating entity
• Eventually, completely monitored systems may safely operate with reduced or even without conventional safety margins to permit an optimized design reducing overall material volume and weight and thus supporting conservation of valuable energy.

2. The Dawn of a New Era

Intelligent, sensor and actuator equipped materials and components will ultimately revolutionize future technical developments. Within a historical perspective (see Figure 1), we may speak of a new era of technical evolution. In general, the nineteenth century was described as the industrial age, characterized by machines replacing human muscle power. Technical developments and inventions, established many years prior, were the prerequisite. For example, Heron of Alexandria was an important geometer and worker in mechanics who invented many machines including a steam turbine, it is believed, in 75 AD. The development of the modern steam engine, however, is attributed to Thomas Newman and James Watt.

During the industrial age, communications evolved from a simple telegraph to the electromagnetic Morse Telegraph or the Teleautograph attributed to Elisha Gray and patented in 1888. In recognition of their contributions to the development of wireless telegraphy the 1909 Nobel Prize in Physics was awarded to Guglielmo Marconi and Karl Ferdinand Braun. Yet, it took almost 100 years to cultivate this technique and to make it an essential part of today’s life. The information technology (IT) era gives the capability to generate and transmit massive amounts of information and data at any time at high-speed transfer rates, and thus provides an additional tool for system management.

![Figure 1. The Dawn of a New Era](image-url)
With the beginning of the new era, machines and technical systems that have “sensing organs” for self-monitoring and monitoring and diagnosis of the surrounding environment and potentially self-repairing capabilities will be developed. This will help to relieve the burden of many human decision-making processes, necessary to safely and reliably operate technical systems and installations. The future will surely have a better name for this technological period, but we will assign, for now, a working title, the “Age of Decision”.

What we currently call SHM will surely be just the beginning of a technological advance, which will have a similar revolutionary impact on the everyday life as did Information Technology.

3. SHM, Why Now?

The idea of continuous condition monitoring using sensors is not new, but is effectively used at present. For several decades, critical components of nuclear power plants\(^{(1)}\), chemical plants and similar installations for example, have been continuously monitored using sensor systems. Sensors have also been used for real-time monitoring of manufacturing processes\(^{(2)}\). More complex techniques, such as ultrasonics, have exhibited a high price tag for a permanent installation and routine maintenance in economically oriented production plants. In addition, conventional ultrasonic equipment, as we know it, is unsuitable for the application in vehicles and lightweight constructions due to its weight and size.

Powerful digital signal processors and wireless communication technology permitting the integration of small sensors and sensor systems into parts and components without complex wiring have been available for a few years\(^{(3)}\). The number of operations performed by a digital signal processor per second in 1990 will be multiplied by a factor of more than one thousand by the year 2010; available memory capacity will increase by a similar amount. The costs for such systems, however, will be reduced by a factor of a hundred, even ignoring the rate of inflation\(^{(1)}\). Crucial for (energy) self-sufficient systems is the reduction of the power consumption, which will be reduced to by a factor of ten thousand to 0.001 watt (1 mW) at one million operations per second.

These significant technical improvements permit not only the incorporation of sensors but also complex measurement systems into very small components with dimensions of just a few cubic millimeters, much smaller than the systems contained in the relatively voluminous enclosures introduced just a few years ago\(^{(5,6)}\). In addition, and in contrast to previous systems, today’s intelligent sensor systems operate at low power consumption rates, where power is provided by long-life batteries or energy harvesting systems\(^{(7,8)}\). Wireless interfaces provide for data communication and system control (Figure 2).
Besides continually increasing processing speeds, memory capacities, and wireless communication capabilities, combined with reduced energy consumption and declining component pricing, another advance, namely the capability of worldwide networking supported by system specialists, can be added. This feature allows all information and data contained in memory are available for evaluation either at the local lab or at worldwide locations in real-time.

4. The Concept

The concept of a typical SHM system is schematically depicted in Figure 3 below. A multitude of sensors are used to monitor operating and material conditions during operation and/or periodically during immobilization, e.g. aircraft during taxiing or refueling. The sensor systems are networked and communicate with each other. The installation or the vehicle maintains a neural system that can indeed be compared to the human nervous system. The most significant difference to conventional nondestructive technologies is that all sensor systems are permanently installed (integrated) into the structure. Acquired data are locally available and also can be transmitted to external systems and/or monitoring stations using wireless communication interfaces allowing continuous or periodic scanning.
Sensor systems can be applied as local monitoring systems to identify crack initiation and/or growth in critical locations or can be used to monitor entire structural components and subassemblies; fiber-optical sensors are currently under development to provide further support\(^\text{(10)}\). Acoustical systems, based on “guided waves” technology, can also be efficiently applied\(^\text{(11)}\). The acquired data have to be pre-processed, typically by sensor-integrated signal processors, prior to performing final data analysis, which is usually done at a relay station or at the monitoring station. Information and resources, available on the internet, can be used for modeling of nondestructive techniques (NDT) and/or modeling of the structure under investigation and thus permit for an integrity statement of complex installations and systems in real-time.

To successfully develop and apply such SHM technologies, it is required that the technical and scientific progress in various areas of expertise are vigorously investigated and exploited. New measurement techniques, based on traditional NDT methods, will be required to provide information and data about material characteristics, material alterations and material discontinuities. The efficiency of the entire system largely depends on the progress in microprocessor and data storage technologies. The longevity and reliability of such sensor platforms is currently an unsolved problem\(^\text{(12)}\).

SHM systems will become a commercial success if low-cost sensor systems can be applied in a simple manner, which requires new ideas and concepts for the packaging of integrated circuits assemblies, including polymer electronics. New data acquisition and signal processing techniques, such as “Acoustic Tomography”\(^\text{(13)}\) or “Random Acoustic Noise Technique” (RANT)\(^\text{(14)}\), must be developed. Both techniques utilize noise emissions and operating noise for component reconstruction and flaw detection, similarly to passive radar systems.
New robust sensors and techniques to embed such sensors into structures must be developed. Fiberglass systems or piezo-electric systems based on fiber structure are currently favored. It is of utmost importance that the embedded sensors do not impact the integrity of the component or part. Composite materials are suitable for embedding of fiber structure sensors, which allows the entire part to develop sensory properties.

Programming of individual network nodes is time-consuming, manpower intensive and costly. Therefore, new networking concepts, allowing the automated integration of any quantity of sensor systems and the toleration of loss of individual systems, will be required. Telemetric techniques to facilitate data transfers between individual nodes, SHM systems and the outside world are currently under development.

In addition, new ideas to supply adequate power for such systems are also needed. Efficient, powerful battery systems, promising several years lifetime are currently under development. Piezo-electric or magneto-inductive “energy harvesting systems”, thermo-electric generators or other methods are also under discussion. Passive systems, receiving energy from external sources or through magnetic field irradiation\(^{(\text{15})}\) are also promising alternatives.

Data evaluation and disposition of results will be a key aspect. The acquired signals have to provide all information necessary to measure material structure, material characteristics and resulting discontinuities to assess integrity and to predict continued operation lifetime or dictate the replacement of the monitored part or component.

SHM systems are not limited to complex electronic solutions and also allow for simple alternative approaches. NASA, for example, has developed a protective coating system that incorporates fluorescent materials, making damage or cracking of the protective coating visible under fluorescent light\(^{(\text{16})}\).

Detailed questions pertaining to actuator and sensor materials, i.e. adaptive materials and components, are not discussed in this paper. However, adaptive materials are also a very important element of the development\(^{(\text{17})}\). (Adaptive materials are materials with actuator-like capabilities i.e. materials that change their form or shape triggered by external or electrical influences for example, piezo ceramics\(^{(\text{18})}\), shape memory alloys\(^{(\text{19})}\) and self-repairing coatings\(^{(\text{20})}\)).

5. Roadmap to Success

The success of this new technology depends, as described above, on a multiplicity of technical developments. The most important resources are provided by conventional (classic) “Condition Monitoring”, nondestructive testing methods and techniques, sensor technology and structure modeling (to assess and estimate reliability and lifetime of installations and components). Various lines of actions with current stages of development are summarized in Table 1 below.
### Table 1. SHM Resources

<table>
<thead>
<tr>
<th><strong>Condition Monitoring</strong></th>
<th><strong>Detection Principles</strong></th>
<th><strong>Operation Monitoring Conditions</strong></th>
<th><strong>Recent Trends</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>To be observed</strong></td>
<td><strong>Fiber Bragg Grating</strong></td>
<td><strong>Usually passive systems</strong></td>
<td><strong>Sensor integration in structure</strong></td>
</tr>
<tr>
<td>Vibrations</td>
<td>Vibration pick-ups</td>
<td><strong>No external stimulation/</strong></td>
<td><strong>Sensor Networks, Telemetric Systems</strong></td>
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<tr>
<td>Stress</td>
<td>Strain Gages</td>
<td><strong>No transmission of signals</strong></td>
<td><strong>Smart Structures</strong></td>
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<tr>
<td>Temperature</td>
<td>Acoustic emission</td>
<td></td>
<td><strong>Self-Repair</strong></td>
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<td>Fatal damage</td>
<td>Visual (CCD’s)</td>
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<tr>
<td>Completeness/Integrity</td>
<td>IR Imaging</td>
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<td>RFID’s</td>
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<tr>
<td><strong>Operation Monitoring</strong></td>
<td><strong>Recently</strong></td>
<td><strong>Sensor integration in structure</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Smart Structures</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Self-Repair</strong></td>
<td></td>
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<tr>
<td><strong>Nondestructive Evaluation</strong></td>
<td><strong>Detection Principles</strong></td>
<td><strong>Localization of Flaws, Damage and Degradation and Material Properties</strong></td>
<td><strong>Recent Trends</strong></td>
</tr>
<tr>
<td><strong>To be observed</strong></td>
<td><strong>Ultrasound</strong></td>
<td><strong>Usually Active Systems</strong></td>
<td><strong>New Techniques</strong> (Optical Techniques, Terahertz)</td>
</tr>
<tr>
<td>Material Flaws</td>
<td>X-and g-rays</td>
<td><strong>For Quality Assurance</strong></td>
<td><strong>Non-contact Techniques</strong></td>
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<tr>
<td>Cracks, Wall-Thinning</td>
<td>Eddy Current</td>
<td><strong>Periodic Inspection</strong></td>
<td><strong>Miniaturization</strong></td>
</tr>
<tr>
<td>Internal Volumetric</td>
<td>Magnetic Flux Fields</td>
<td><strong>No Transmission of Signals</strong></td>
<td><strong>Multi Probe and Local Probe Techniques</strong></td>
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<tr>
<td>Flaws</td>
<td>Dye Penetrant</td>
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<td><strong>Imaging and Tomographic Reconstruction</strong></td>
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<td>Residual Stresses</td>
<td>Active Thermography</td>
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<td>Inherent Material</td>
<td>Micro-waves</td>
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<td>Properties</td>
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<td>Microstructure</td>
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<tr>
<td><strong>Modeling, Reliability, Service Strength</strong></td>
<td><strong>Methods</strong></td>
<td><strong>Lifetime Prognosis</strong></td>
<td><strong>Recent Trends</strong></td>
</tr>
<tr>
<td><strong>To be considered</strong></td>
<td><strong>Analytic Solutions</strong></td>
<td><strong>Based on Material Properties</strong></td>
<td><strong>Incorporation of In-service Data</strong></td>
</tr>
<tr>
<td>Static and dynamic</td>
<td><strong>Finite Element Codes</strong></td>
<td>According to Design Rules</td>
<td><strong>By Embedded Sensors</strong></td>
</tr>
<tr>
<td>modeling of:**</td>
<td><strong>Finite Volume Codes</strong></td>
<td><strong>Experimental Verification of Load Conditions (CMS) and Material Properties/Flaws (NDE) required</strong></td>
<td><strong>Adaptive Structures</strong></td>
</tr>
<tr>
<td>Thermal and Mechanical loads</td>
<td><strong>Nano-simulation</strong></td>
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<td><strong>Health Control</strong></td>
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<td>Operating Conditions</td>
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<td><strong>Self-healing Materials and Structures</strong></td>
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<td>Elastic/Plastic Material Behavior</td>
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<td>Temperature Fields</td>
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<td>Stress Distributions</td>
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<td>Damage Progression</td>
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<tr>
<td><strong>Sensor Technology</strong></td>
<td><strong>Sensor principles</strong></td>
<td><strong>Transformation of chemical or physical quantities into electric signals</strong></td>
<td><strong>Intelligent Sensors with Incorporated Signal Analysis, Data</strong></td>
</tr>
<tr>
<td><strong>To be measured</strong></td>
<td><strong>Resistance/Conductivity</strong></td>
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<tr>
<td>Temperature</td>
<td><strong>Piezoelectricity</strong></td>
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<tr>
<td>El./Magnetic Fields and Radiation</td>
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</table>

**Sensor Technology**

- Temperature
- El./Magnetic Fields and Radiation
<table>
<thead>
<tr>
<th>Monitoring of:</th>
<th>Storage</th>
</tr>
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<tbody>
<tr>
<td>• Loading Conditions</td>
<td>• Power Management</td>
</tr>
<tr>
<td>• Distances and Locations</td>
<td>• Multi-sensors, and Sensor Networks</td>
</tr>
<tr>
<td>• Environmental Parameters</td>
<td>• Self-calibrating and Self-diagnosis</td>
</tr>
<tr>
<td>• Active Degradation Processes</td>
<td>• Miniaturization and Energy Independence</td>
</tr>
</tbody>
</table>

- Pressure, Force, Vibration, Acceleration
- Voltage, Current
- Chemical Composition
- Damage Processes (corrosion)
- Thermoelectric Effect
- Electric Induction
- Photoelectric Effect
- Spectroscopy
- Electro-magnetic Noise
- Thermoelectric Effect
- Electric Induction
- Photoelectric Effect
- Spectroscopy
- Electro-magnetic Noise

The combination of the resources and expertise mentioned above has formed the Structural Health Monitoring (SHM) approach, see also Figure 4 below.

**Figure 4.** SHM, a Multi-disciplinary Assignment

**Figure 5.** Prototype Monitoring System for High-Speed Trains
Sensor node and monitoring system prototypes are available in various laboratories worldwide and initial testing has been performed. All these systems are based on the concept of classical condition monitoring. Wind generators (wind power stations) are using fairly simple versions of such systems on a large scale\(^{(22)}\). An example for monitoring hollow shaft wheel sets of high-speed passenger trains, using a wheel set axle integrated sensor system, is depicted in Figure 5. This sensor system primarily monitors wheel-generated noise and is capable of detecting cracking in wheels and axle shafts. Acquired data are processed during the ride and telemetrically transferred to operations control when the train passes the relay station\(^{(23)}\). This type of monitoring system will be tested in the coming years on a large scale. Similar ambitious objectives have been established by the public aviation industry\(^{(23)}\). Prototype systems to monitor corrosion and fatigue damage of military aircraft are currently being tested\(^{(24)}\). These monitoring systems are capable of directly measuring material damage and/or stresses and can also detect damaging conditions, such as excessive load cycles and/or corrosive strains.

The ultimate goal for SHM is to predict the lifetime of the monitored installations and components. Simple monitoring techniques have been in use in automobiles for a number of years and the automotive industry is pushing hard for the development and integration of state-of-the-art monitoring systems.

### 6. Our Projection

As discussed at the beginning, all of the developments described in this paper are only the start of a new industrial era of technical systems that are capable of assessing their current conditions and making decisions about continued operation by applying their sensory and actuator capabilities. Large-scale self-repairing materials, systems and installations will be available in a few years, initially for the self-repair of protective coatings or similar applications\(^{(20)}\); small robotic systems for self-diagnosis and repair are also being developed.

Figure 6 below presents our projection of the development trends for the next twenty years. Based upon available plans of the Deutsche Bahn AG, aviation industry, automotive industry, wind power generation industry and many others, we assume that more sensor types will be developed with the main emphasis on intelligent sensors for signal processing and data communication. Sensors will increasingly function in self-organizing network nodes.

A very important trend will be the development of actuators and smart materials (materials with sensory and actuator capabilities). A quite popular product currently made of such material is the diesel fuel injection pump, which permits reduced fuel consumption at higher performance levels\(^{(25)}\).
Figure 6. Our Development Projection

Today’s sensor technologies primarily serve as a monitoring tool in addition to periodical in-service inspections and maintenance - future technologies will be able to promptly react to occurrences and identified events. For example, if damage is detected, the handling of a vehicle could be changed in such a way that the damaged structure is subjected to less (or minimal) load. In addition, actuating behavior for the reduction of damages, for example shock absorption or the optimization of load stresses (load compensation) will be used in the future. This technology is called “Structural Health Control” (17). Further advanced solutions, such as self-healing or self-repairing structures, as we know for example in biological systems, will have a huge future potential.

7. Summary

Advances in sensor technology and microelectronics will permit the employment of economical and powerful sensor systems to continuously monitor industrial installations and plants, vehicles and other equipment. At present, we are at the stage of laboratory prototypes and full-scale tests. Local sensor systems that monitor defined critical areas of a vehicle will be available in this decade on a broad basis. Realistic plans predict that global monitoring of vehicles and industrial installations will also be available within the next ten years. This approach will lead, apart from increased usage and higher safety of the systems, to a better utilization of materials and energy at lower operating costs. Completely new design rules, which will consider permanent and continuous monitoring, have to be established and will lead to radically new technical solutions. We are therefore at the beginning of a new technological era. Machines and technical installations will diagnose themselves, react to differing load states and exhibit the ability for self-repair. Properties
that nature has assigned to living creatures and plants, will be designed, manufactured and installed into mechanized industrial equipment.

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