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Introduction to Smart Technologies

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1.1 Smart Technologies – 30 Years of History

The term *smart technologies* (Smart-Tech) is understood as a generalization of the concept of *smart structures*. Smart technologies encompass mechanical systems equipped with sensors, actuators and pre-programmed controllers, which allow a structure to adapt to unpredictable external loading conditions. The concept of smart technologies requires the knowledge about the mechanical system itself, embedded sensors and controllable devices (usually based on *smart materials*), and driving electronics with integrated software, which adds the *intelligence* to the system.

Technological developments in the field of smart materials (modifying their properties, e.g. due to variation of the electric or magnetic field) and computational techniques have reached a point in which their synergy has a significant impact on the applicability of the interdisciplinary concepts of smart technologies to real structures (*smart structures*). The material science has led to the theoretical and experimental development of multifunctional materials (e.g. piezoelectric ceramics, shape memory alloys, magnetorheological fluids (MRFs), magnetostrictive materials). Furthermore, the development of fast and miniaturized microprocessors has enabled the design of embedded systems with distributed control capabilities. The final integrated product is composed of the following items:

- (1) a distributed sensing system (e.g. based on piezoelectric transducers) able to monitor the structural response;
- (2) actuators (e.g. utilizing MRFs) able to modify structural properties and
- (3) control units able to realize a pre-designed strategy.

Such systems can be very effective in many applications, including structural health monitoring, mechanical impact absorption, damping of vibration and noise reduction.

Intelligent structures became the object of scientific research (mainly as hypothetical solutions) as a result of new demands that came from the space engineering in the 1970s and 1980s. For example, the problem of shape preservation of a parabolic antenna, launched in space, is

not a trivial task. The thermal shock that occurs while passing through the Earth's shadow can cause vibrations, which are very difficult to be damped. These vibrations are induced due to the high flexibility of space structures, resulting in their low natural damping. As a remedy, intelligent systems, able to mitigate these vibrations, had to be invented. This shape (and vibration) control problem can be formulated by making use of highly responsive piezo-sensors and piezo-based actuators. The above-mentioned shape control problem requires work to be done against the resisting structure, using actuators. In the case of large civil structures, this actuation leads to substantial energy consumption, which cannot be supplied instantly. Consequently, the applications for this type of smart structure are significantly limited. Nevertheless, an important class exists of large real structures that can be effectively controlled with smart devices, consuming little power. Such structures can be called *adaptive structures* (instead of *active structures*). They are equipped with the dissipative kind of actuators (or dissipators) only. The field of their application is, for instance, the *adaptive impact absorption* (AIA), in which a structure equipped with controllable dissipators has to absorb optimally the energy coming from external extreme loads.

In the 1990s, the smart structure concept was under development through various lab-scale demonstrations of fully active, but very flexible systems, dynamically controlled with piezo-patches. Adaptive (semi-active) systems were also applied effectively to very large real civil structures (e.g. tall buildings in seismic areas or suspension bridges with MRF-controlled dampers).

Currently, the main stream of worldwide research and development activities in the field of smart structures is focused on *structural health monitoring* (SHM) and *load identification* (mostly applied to civil, mechanical and aerospace structures). There are several periodically organized international conferences [1–5] and scientific journals devoted to the subject. These academia-industry meetings, gathering various engineering communities, demonstrate the rapid development of SHM hardware solutions, accompanied by a relatively slow progress of new software tools. Researchers do have access to huge databases collected via numerous installations (mostly the large bridges monitored in Japan and South Korea), but the *soft computing tools* (e.g. based on *neural networks* or *genetic algorithms*) seem to have encountered limitations in application to large real structures. The *structural control* is the second field of application for smart technologies (e.g. damping of vibration [6] in antiseismic structures or in suspension bridges by MRF dampers). Dedicated international conferences are periodically held on structural control [7, 8], including some SHM issues as well. There are also cyclic events strongly related to the SHM and structural control topics [9–13]. In general, the interdisciplinary solutions can provide some extraordinary properties, thus mechatronic ideas, for example, are more and more frequently applied in structural mechanics. Nevertheless, there are still new areas open to potential applications as well as possibilities of improvement in already existing solutions. An important example is the design of vehicles with improved *crashworthiness*. For example, new euro codes, imposing high survivability requirements in crash scenarios, are under preparation. An increased interest can therefore be expected in the development of effective methods (including hardware devices and software tools) for the design of safe, crash-resistant vehicles.

New, emerging areas for the application of smart technologies are autonomous systems able to:

- monitor environmental conditions;
- identify extreme loads in real time;
- adapt to overloading by proper tuning of controllable dissipators;

- monitor structural health after the reception of impact;
- facilitate a decision on further use of the structure (self-repair if possible, post-impact inspection, reinforcement or rebuilding).

Particularly challenging problems to be solved are the following:

- distributed sensor systems for monitoring large structures;
- wireless sensors and data transmission;
- fast programmable controllers for embedded, distributed systems;
- long-life power sources and energy harvesting;
- fastly responding actuators with high stroke and blocking force;
- driving electronics allowing for instantaneous generation of magnetic fields;
- software tools processing effective algorithms (e.g. solving dynamic, inverse problems), aiming at identification of the current state of structural health.

1.2 Smart-Tech Hardware Issues

1.2.1 Structural Health Monitoring

The term *structural health monitoring* (SHM) refers to an important and fast-developing area of smart technologies. Its objective is the identification of damage (or load) by investigating structural responses due to environmental (ambient) or known excitations. In SHM systems, modern sensing technologies are employed to provide accurate measurements of structural responses. The results of the measurements can be subsequently analyzed by numerical algorithms in order to identify damage in the structure. Generally, modern SHM hardware systems consist of sensors, a data acquisition and processing block, a communication item and a main computer center. Physical quantities typically measured in vibration testing include accelerations or strains. In addition, measurements of temperature, humidity and wind velocity may be required to quantify the environmental conditions. Depending on the physical quantities to be monitored, the type of sensor is selected accordingly, i.e. accelerometers, tensometers, etc. A challenging problem is to determine the minimum number of required sensors and their optimal placement.

Probably the most common measuring devices used in SHM are the piezoelectric transducers [14] because of their outstanding electromechanical properties, relatively low price, and both actuating and sensing capabilities. They have been used for years in classical *nondestructive testing and evaluation* (NDT/E) methods like ultrasonic testing or acoustic emission. The direct piezoelectric effect, utilized in sensors, is present when a mechanical deformation of the piezoelectric material produces a proportional change in the electric polarization of that material (electric charge appears on opposite faces of the material). The converse piezoelectric effect, utilized in actuators, means that an acting external electric field induces proportional mechanical stress in the piezoelectric material (the material is deformed when an electric voltage is applied). A rather restricted number of piezoelectric materials have been found to be suitable for transduction elements in piezoelectric sensors. Basically, natural crystals (e.g. quartz, tourmaline) and synthetic single crystals (e.g. gallium ortho-phosphate, crystals of the CGG group), piezoelectric ceramics (e.g. lead–zirconate–titanate, denoted as PZT) and thin films (e.g. polyvinylidene fluoride, denoted as PVDF) can be used. Piezoelectric materials used in sensors combine excellent mechanical properties with a high piezoelectric sensitivity at a low production cost. They have a number of advantages, which makes them particularly suitable for dynamic measurements. Piezoelectric sensors have extremely high stiffness (their

deflections are usually in the μm range), high natural frequency (hundreds of kHz), wide measuring range and a wide operating temperature range. The crystal-based sensors have very high stability whereas the ceramic-based ones can be produced in commercial quantities. Quasi-static measurements are possible with sensors having single crystals as transduction elements. Piezoelectric sensors can directly measure force, strain, acceleration and pressure. Sometimes the piezoelectric transducers are used for both actuation and sensing of a structural response simultaneously. The electrical impedance of the transducer is directly related to the mechanical impedance of the structure on which the transducer is mounted. Changes of structural properties such as stiffness, mass and damping can be monitored this way.

The fiber optic sensors [15] have a great potential to become widely used instruments in the field of SHM. Typical electrical strain gages are small and very accurate strain-measuring devices. However, they generally have a small dynamic range and are affected by environmental conditions such as moisture and temperature. Modern optical fibers are composed of high-silica glass doped with some oxides to achieve a required refraction index. An optical fiber consists of a core encapsulated in a cladding with a smaller refraction index. This enables total internal refraction at some incidence angle of entering light. Optical fibers can be generally divided into two types: multimode and single mode. Of special importance in strain sensor technology are single-mode optical fibers. Single-mode fiber limits its guidance capability for a chosen wavelength to one mode thanks to small diameter of the core and small difference between the core and cladding refraction indices. In practice, however, instead of just one mode, two orthogonally polarized, strongly coupled modes are carried by most commercially produced fibers. This effect, called birefringence, is often preferable as it helps the fiber to maintain the polarization of a guided wave and transmit it long distances. Light launching into a single-mode fiber of small core is difficult and favors a light source with highly directional output, e.g. a light emitting diode or injection laser diode. The major division of the fiber optic sensors distinguishes the interferometric sensors for outside (i.e. surface) application and *fiber Bragg grating* (FBG) sensors for inside application (i.e. embedded in the structure). The most widespread interferometric sensors interrogate a measurand-induced change of phase in the light propagating along a single-mode optical fiber. Several different layouts of interferometric sensors may be used, depending on the arrangement of optical paths. The most common configurations, based on phase change analysis, are the Michelson and Fabry–Perot interferometers. Interferometric optical fiber sensors provide high-sensitivity measurements. They require a special signal recovery technique (demodulation) to perform absolute measurements. Development of low-cost fabrication methods that do not compromise the strength and fatigue life of the optical fibers should facilitate the wide use of the sensors. The FBG sensors are highly sensitive devices as well. Their manufacturing process is automated and ensures no strength loss of the optical fiber. The intracore Bragg grating fiber optic sensor relies on the narrowband reflection from a fiber segment of periodic variations (gratings) in the core index of refraction of a single-mode fiber. If FBG sensors are used with the ratiometric demodulation system, they can build a robust, absolute-measurement, low-cost sensing system, which can be integrated on an optoelectronic chip, easily interconnected with the structure.

The *laser Doppler vibrometer* (LDV) can also be applied to reliable measuring of vibration characteristics (e.g. displacements, velocities) of large structures, even under a low-level excitation such as ambient vibration. The LDV is an indispensable tool whenever direct contact with the investigated object is impossible or undesirable.

Today's conventional monitoring systems have their measuring points wire-connected to the centralized data acquisition unit through coaxial cables. The sensors provide analog time signals, which need to be sampled and digitized for use in modern discrete-signal-processing

Figure 1.1 A bridge with a cable-based SHM system

systems. As the analog signal sometimes travels a long distance from the sensor to the data acquisition unit, it may become noisy and degrade with the increasing cable length. A conventional SHM system, consisting of sensors, preamplifiers, a preliminary signal processing unit, an analog–digital (A/D) converter, centralized data acquisition and storage unit, is depicted in Figure 1.1. An alternative for the conventional SHM system can be obtained by merging some up-to-date technologies, which enable improved data acquisition and transmission. *Microelectromechanical systems* (MEMSs) for SHM are miniature electromechanical sensor and actuator systems fabricated in numerous series, using the processes of *very large system integration* (VLSI) technologies. Combining the advanced MEMS sensors with microcontrollers, an inexpensive, compact and intelligent sensing system can be made without the necessity to rely on the expensive data logger and the A/D transform interface. Modern, intelligent MEMSs equipped with microcontrollers should evolve towards devices able to:

- provide wireless communication between the sensor and the data acquisition unit by installing special chips (already accomplished);
- handle large amounts of data and filter out only the relevant information by utilizing programmable microcontrollers with dedicated software (to be accomplished).

Such remote intelligent monitoring system is expected to reduce the monitoring cost significantly. An example of a modern SHM system, with enhanced functionality thanks to the intelligent data processing plus wireless communication between sensors and the centralized data storage unit, is shown in Figure 1.2. However, many challenges associated with developing wireless SHM systems include restricted power consumption, data fidelity during wireless communication, real-time data acquisition from multiple sensing points under a limited communication bandwidth and the difficulties in time synchronization.

Although many real-time monitoring and control systems are designed to be computer based, the final decision on continued or suspended operation of a structure/system should be taken by qualified staff. The fast-growing databases, containing different kinds of data, have been the incentive to develop the *decision support systems* (DSSs), which facilitate on-line monitoring of the structure/system by using artificial intelligence methods, e.g. *case-based reasoning* (CBR).

Figure 1.2 A bridge with a wireless SHM system

1.2.2 Adaptive Impact Absorption

The term *adaptive structures* refers to *controllable structures*, equipped with pliant actuators, which modify (in real time) the mechanical properties of the structure exposed to extreme loads in such a way that no externally generated control forces are introduced. As a consequence, there is no need for an energy source to control the performance of the actuators (except for the low-energy source required to power the pliant dissipators). This class of *smart structures* is much more likely to be applied in civil and mechanical engineering, where the control process is restricted to a ‘smart’ strategy of dissipation of the strain energy accumulated due to the external load. Actuators take the form of energy dissipators with controlled characteristics (e.g. with the *yield stresses* as control parameters), which trigger plastic-like behavior (yielding) in the overloaded zones. The predetermined optimal distribution of plastic-like properties in structural elements (realized by *structural fuses* e.g. in the form of controlled pneumatic or hydraulic valves) can significantly increase the total energy dissipation level and improve the overall structural performance.

Consider an example of the adaptive chassis of a passenger car, shown in Figure 1.3(a). Here, the plastic-like behavior in the truss-like suspension system can be controlled by quick opening and closing of the hydraulic ultimate valves. For example, assume that the plastic limits in the adaptive elements cannot exceed the value σ^u . If the limit pressures, which trigger the opening of the valves A_1 and A_2 (see Figure 1.3(b)), make the condition $\sigma^* < \sigma^u$ satisfied, then the overall characteristic of the adaptive element will take the form shown in Figure 1.3(c). A similar effect can be realized by using an MRF instead of controllable valves.

Numerical tests [16] have demonstrated high efficiency of the above concept for the impact energy absorption of a railway car crashing against a rigid wall. The obtained results show that for an impact velocity of 25 m/s, safe adaptation of the chassis is possible using just passive elements, i.e. where the plastic limits σ^* are assumed to be constant and not controlled. However, by adopting a control strategy for the process, which allows the plastic limits σ^* to be tuned in each adaptive element, the maximum safe impact velocity is increased to 38 m/s. Applicability of the adaptive concept to the design of structures for extreme loads, especially for impacts (cf. Chapter 5) and for vibration control (cf. Chapter 7), is demonstrated in this book. Some applications to the design of civil and mechanical structures in particular are also presented.

Figure 1.3 (a) Two-layer adaptive suspension system, (b) model of an adaptive hydraulic absorber, (c) characteristic of the adaptive element

The hardware required for AIA systems includes accelerometers, force, pressure and strain sensors. Some parts of the instrumentation are similar to SHM systems, but the necessary items are a microcontroller, feedback units and activating elements, i.e. actuators (see Figure 1.4). The microcontroller is a computer on a chip and is used to control electronic devices. A typical microcontroller contains all the memory and interfaces needed for a simple application, whereas a general-purpose microcontroller requires additional chips to provide these functions. Thus the typical microcontroller is a kind of microprocessor characterized by self-sufficiency and cost-effectiveness, in contrast to the general-purpose microcontroller (the kind used in a personal computer (PC)). The use of a microcontroller significantly reduces the number of chips and the amount of wiring in an AIA system.

For the last decade a vivid debate has run about the advantages and disadvantages of programmable logic controllers (PLCs) compared to PC-based ones. While the technological differences between the PLCs and PCs disappear, with PLCs using commercial off-the-shelf

Figure 1.4 Block diagram of a basic AIA system

hardware and PCs incorporating real-time operating systems, a new class of controllers, the programmable automation controller (PAC), is emerging. Although many industrial applications are solved with traditional tools, there is a strong demand for simple low-cost PLCs. This has been an incentive for the growing production of low-cost micro-PLCs with digital input/output (I/O) using ladder logic. Most PLC users create PAC software by adding new functionality such as Ethernet communication, motion control and advanced algorithms into the existing architecture. PACs can directly take high-accuracy measurements, which are then passed directly into their control systems for immediate processing. In the AIA applications, it is extremely important to collect high-speed measurements for loads and vibrations. PACs represent the latest achievement in programmable controllers. The future for PACs is the incorporation of embedded technology. A challenging issue is the ability to design software in order to define hardware.

The field programmable gate arrays (FPGAs) [17] are electronic components commonly used by manufacturers to create custom chips, allowing the 'intelligence' to be placed in new devices. These devices consist of:

- configurable logic blocks able to perform a variety of functions;
- programmable interconnections acting as switches to connect the function blocks;
- I/O blocks that pass data in and out of the chip.

FPGAs are comparable to having a computer that literally rewires its internal circuitry to run a specific application. For example, one of the PAC platforms, named the Compact FieldPoint (<http://www.ni.com/pac/cfp.htm>), consists of hot-swappable analog and digital I/O modules and controllers with Ethernet and serial interfaces. The Compact FieldPoint network communication interfaces automatically publish the measurements through an Ethernet network. Another PAC platform named CompactRIO (<http://www.ni.com/pac/crio.htm>) is an FPGA-based reconfigurable control and acquisition system, designed for applications that require a high degree of customization and high-speed control. The architecture combines a real-time embedded processor for complex algorithms and custom calculations with a reconfigurable I/O (RIO) FPGA core.

1.3 Smart-Tech Software Issues

Smart technologies include not only the hardware devices but also the accompanying software tools, realizing smart strategies of structural monitoring and control. The numerical tools for the SHM and the design of adaptive structures, presented in this book, are often based on the *virtual distortion method* (VDM) (see Chapter 2). The VDM has been developed especially for a fast reanalysis, sensitivity analysis and control of dynamic structural responses. The presented software packages (see Chapters 3, 4 and 6) are numerically very effective and original.

In the design of structures for crashworthiness, present-day numerical simulation tools used in routine engineering practice focus on precise calculation of the crashing response of the base structures, but offer little guidance in the design process of optimal, energy-absorbing systems. On the contrary, as a result of the approach presented in this book (see Chapter 6), the optimal material distribution and nonlinear material characteristics could be designed (with the help of suitable software packages) for a predicted set of crash scenarios, including side impacts, which are difficult to be absorbed.

The numerical tools developed to design dynamically responding (also in the case of physical nonlinearities) systems can also be applied for damage identification and structural health

monitoring problems. Consequently, Chapter 3 of this book is dedicated to inverse dynamic problems, where the VDM-based sensitivity analysis allows the damage location and intensity to be determined by observation of perturbations in structural responses. A part of Chapter 4 presents a solution of an SHM-related problem of load (location and intensity in time) reconstruction via inverse analysis.

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