Structural Health Monitoring

Edited by
Daniel Balageas,
Claus-Peter Fritzen
and
Alfredo Güemes

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Foreword

The origins of this book date back to a pre-conference course given at the First European Workshop on Structural Health Monitoring, which was held at the Ecole Normale Supérieure of Cachan (Paris) in July 2002. In 2004, this course was extended to form a continuing-education short course lasting three and a half days, organized by the Ecole Normal Supérieure of Cachan.

The motivation of the authors has essentially been to make the information collected for this short course more widely available, especially at the present time, which is characterized by the strong emergence of approaches in the technical community to the problems of Structural Health Monitoring.

The book is organized around the various sensing techniques used to achieve the monitoring. For this reason, emphasis is put on sensors, on signal and data reduction methods, and on inverse techniques, allowing the identification of the physical parameters affected by the presence of the damage on which the diagnosis is established. This choice leads to a presentation that is not oriented by the type of applications or linked to special classes of problems, but presents the broad families of techniques: vibration and modal analysis (Chapter 2), optical fibre sensing (Chapter 3), acousto-ultrasonics using piezoelectric transducers (Chapter 4), and electric and electromagnetic techniques (Chapters 5 to 7).

Each chapter has been written by specialists in the domain of the chapter, who have been working in the field for a long time and have wide knowledge and experience. The authors, who come from the academic world or from research centres, have written their contributions in a pedagogical spirit, so that this book can be easily understood by beginners in the field and by students. Nevertheless, the book aims to present an exhaustive overview of present research and development, giving numerous references that will be useful even to experienced researchers and engineers.

The Editors
D.L. Balageas, C.-P. Fritzen, A. Güemes

Chapter 1

Introduction to Structural Health Monitoring

1.1. Definition of Structural Health Monitoring

Structural Health Monitoring (SHM) aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although this can be altered by normal aging due to usage, by the action of the environment, and by accidental events. Thanks to the time-dimension of monitoring, which makes it possible to consider the full history database of the structure, and with the help of Usage Monitoring, it can also provide a prognosis (evolution of damage, residual life, etc.).

If we consider only the first function, the diagnosis, we could estimate that Structural Health Monitoring is a new and improved way to make a Non-Destructive Evaluation. This is partially true, but SHM is much more. It involves the integration of sensors, possibly smart materials, data transmission, computational power, and processing ability inside the structures. It makes it possible to reconsider the design of the structure and the full management of the structure itself and of the structure considered as a part of wider systems. This is schematically presented in Figure 1.1.

Chapter written by Daniel BALAGEAS.

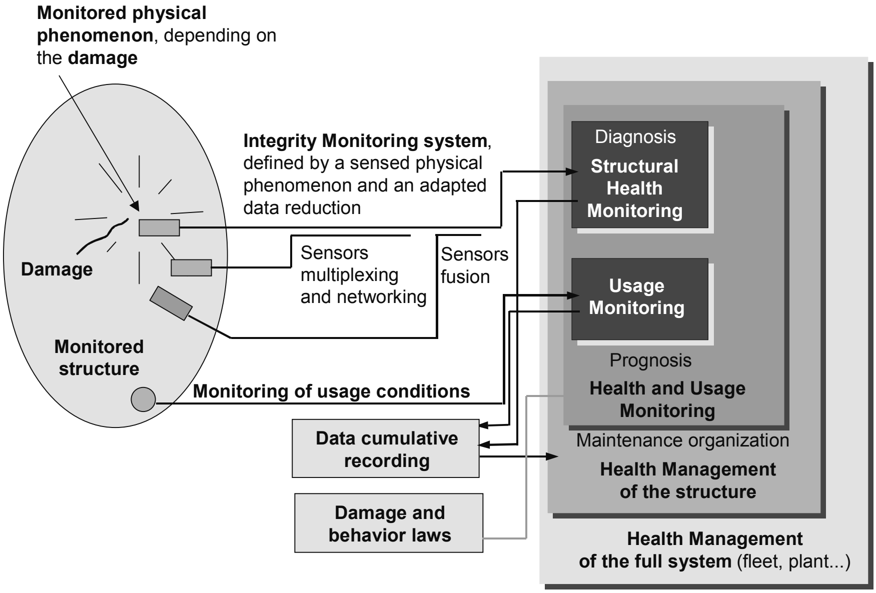

Figure 1.1. *Principle and organization of a SHM system*

In Figure 1.1, the organization of a typical SHM system is given in detail. The first part of the system, which corresponds to the structural integrity monitoring function, can be defined by: i) the type of physical phenomenon, closely related to the damage, which is monitored by the sensor, ii) the type of physical phenomenon that is used by the sensor to produce a signal (generally electric) sent to the acquisition and storage sub-system. Several sensors of the same type, constituting a network, can be multiplexed and their data merged with those from other types of sensors. Possibly, other sensors, monitoring the environmental conditions, make it possible to perform the usage monitoring function. The signal delivered by the integrity monitoring sub-system, in parallel with the previously registered data, is used by the controller to create a diagnostic. Mixing the information of the integrity monitoring sub-system with that of the usage monitoring sub-system and with the knowledge based on damage mechanics and behavior laws makes it possible to determine the prognosis (residual life) and the health management of the structure (organization of maintenance, repair operations, etc.). Finally, similar structure management systems related to other structures which constitute a type of super system (a fleet of aircraft, a group of power stations, etc.) make possible the health management of the super system. Of course, workable systems can be set up even if they are not as comprehensive as described here.

1.2. Motivation for Structural Health Monitoring

Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. In effect, SHM:

– allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures,

– gives the constructor an improvement in his products,

– drastically changes the work organization of maintenance services: i) by aiming to replace scheduled and periodic maintenance inspection with performance-based (or condition-based) maintenance (long term) or at least (short term) by reducing the present maintenance labor, in particular by avoiding dismounting parts where there is no hidden defect; ii) by drastically minimizing the human involvement, and consequently reducing labor, downtime and human errors, and thus improving safety and reliability. These drastic changes in maintenance philosophy are described in several recent papers, in particular for military air vehicles [DER 03], for Army systems [WAL 03] for civil aircraft [BER 03, GOG 03], and for civil infrastructures [FRA 03].

The improvement of safety seems to be a strong motivation, in particular after some spectacular accidents due to: i) unsatisfactory maintenance, for example, in the aeronautic field, the accident of Aloha Airlines [OTT 88] – see Figure 1.2a) – or, in the civil engineering field, the collapse of the Mianus River bridge; ii) ill-controlled manufacturing process, for example, the Injak bridge collapse (see Figure 1.2b)). In both fields the problem of aging structures was discovered and subsequent programs were established. To pinpoint the importance of the problem of structural aging, the following statistic can be recalled: bridge inspection during the late 1980s revealed that on the 576,000 US highway bridges, 236,000 were rated deficient by present day standards [WAN 97].

Nevertheless, analysis of the various causes of aircraft accidents points to the relatively low influence of maintenance deficiency. Figure 1.3 shows that maintenance is only responsible of 14% of hull loss. Furthermore, it should be noted that only 4% of all accidents are due to structural weakness. It can be concluded that, thanks to the introduction of SHM, even an improvement in maintenance and a decrease of structure-caused accidents by a factor of two would lead to a global reduction of accidents of less than 10%, which is far from what is needed to avoid a significant increase in the number of accidents in the near future if air traffic continues to increase.

The economic motivation is stronger, principally for end-users. In effect, for structures with SHM systems, the envisaged benefits are constant maintenance costs and reliability, instead of increasing maintenance costs and decreasing reliability for classical structures without SHM (see Figure 1.4).

Figure 1.2. *Spectacular accidents have motivated the community to improve safety: a) the Aloha Airlines flight 243, April 29, 1988, due to corrosion insufficiently controlled by maintenance; b) the Injaka bridge collapse, July 1998, due to a poorly controlled construction process*

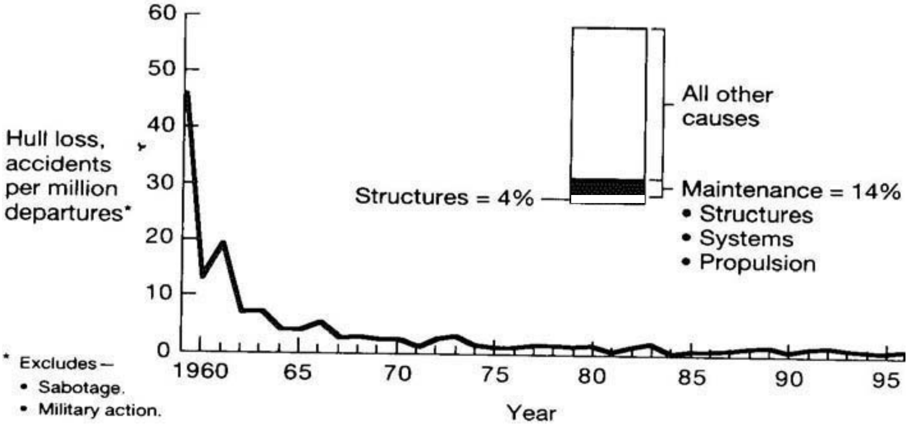

Figure 1.3. *Origin of hull losses: safety record for the worldwide commercial jet fleet, from [GOR 97]*

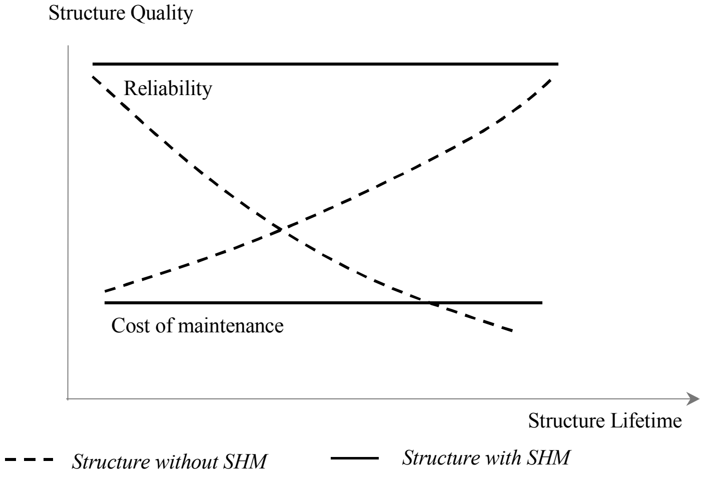

Figure 1.4. *Benefit of SHM for end-users [CHA 02]*

The economic impact of the introduction of SHM for aircraft is not easy to evaluate. It depends on the usage conditions and, furthermore, it is difficult to appreciate the impact on the fabrication cost of the structure. The cost of SHM systems must not be so high as to cancel out the expected maintenance cost savings.

It is easier to evaluate the time saved by the new type of maintenance based on the introduction of SHM. Such an evaluation can be found, for military aircraft, in [BAR 97], who reports that, for a modern fighter aircraft featuring both metal and composite structure, an estimated 40% or more can be saved on inspection time through the use of smart monitoring systems. Table 1.1 presents the figures resulting from this evaluation.

Inspection type	Current inspection time (% of total)	Estimated potential for smart systems	Time saved (% of total)
Flight line	16	0.40	6.5
Scheduled	31	0.45	14.0
Unscheduled	16	0.10	1.5
Service instructions	37	0.60	22.0
	100		44.0

Table 1.1. *Estimated time saved on inspection operations by the use of SHM, for modern fighter aircraft, from [BAR 97]*

Still in the aeronautic domain, there is also a benefit for constructors. Taking into account the permanent presence of sensors at the design stage will permit a reduction in the safety margins in some critical areas. Weight reduction will be then possible, giving higher aircraft performance, lower fuel consumption and greater maximum range.

1.3. Structural Health Monitoring as a way of making materials and structures smart

Since the end of the 1980s, the concept of smart or intelligent materials and structures has become more and more present in the minds of engineers. These new ideas were particularly welcome in the fields of aerospace and civil engineering. In fact, the concept is presently one of the driving forces for innovation in all domains.

The concept of Smart Materials/Structures (SMS) can be considered as a step in the general evolution of man-made objects as shown in Figure 1.5. There is a continuous trend from simple to complex in human production, starting from the use of homogeneous materials, supplied by nature and accepted with their natural properties, followed by multi-materials (in particular, composite materials) allowing us to create structures with properties adapted to specific uses. In fact, composite materials and multi-materials are replacing homogeneous materials in more and more structures. This is particularly true in the aeronautic domain. For instance, composite parts are now currently used or envisaged for modern aircraft (see for instance in Figure 1.6, Boeing's *7E7 Dreamliner* project, which has 50% of its structures made of composites). It is worth noting that this aircraft is the first one in which it is clearly planned to embed SHM systems, in particular systems for impact detection.

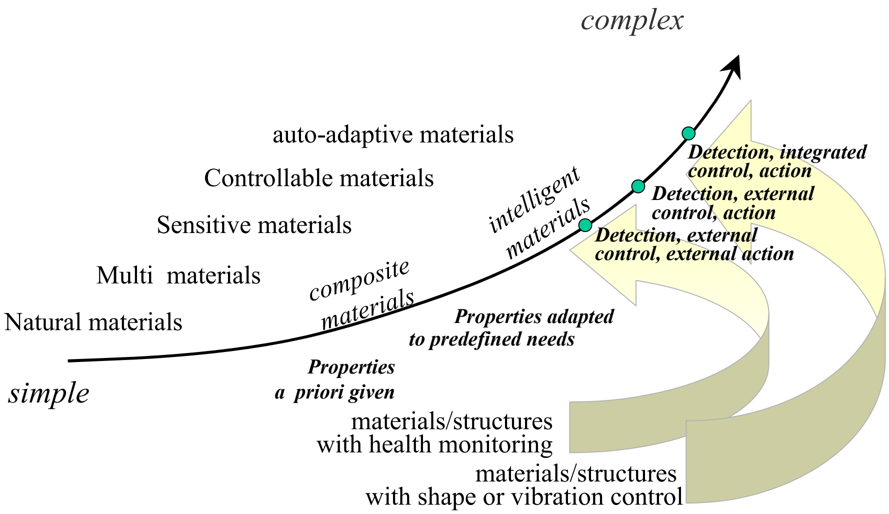

Figure 1.5. *General evolution of materials/structures used by people, and the place of smart structures, including structures with SHM*

The next step consists of making the properties of the materials and structures adapt to changing environmental conditions. This requires making them sensitive, controllable and active. The various levels of such "intelligence" correspond to the existence of one, two or all three qualities. Thus, sensitive, controllable and auto-adaptive materials/structures can be distinguished. Classically, three types of SMS exist: SMS controlling their shape, SMS controlling their vibrations, and SMS controlling their health. It is clear that materials and structures integrating SHM systems belong, at least in the short term, to the less smart type of SMS. In effect, almost all achievements in this field are only intended to make materials/structures sensitive, by embedding sensors. The next step towards smarter structures would be to make self-repairing materials/structures, or at least materials/structures with embedded damage-mitigation properties. For damage mitigation, embedding actuators made of shape memory alloys (SMA) could be a solution that would induce strains in order to reduce the stresses in regions of strain concentration. These SMA actuators could be in the form of wires [YOS 96, CHO 99] or films [TAK 00]. As regards self-healing structures, very few attempts have been made. We could mention, in the field of civil engineering, the existence of self-healing concretes containing hollow adhesive-filled brittle fibers: the adhesive is released when the fibers are broken in the region where cracking occurs [DRY 94]. A similar method can be applied to polymer matrix composites [DRY 96, MOT 99].

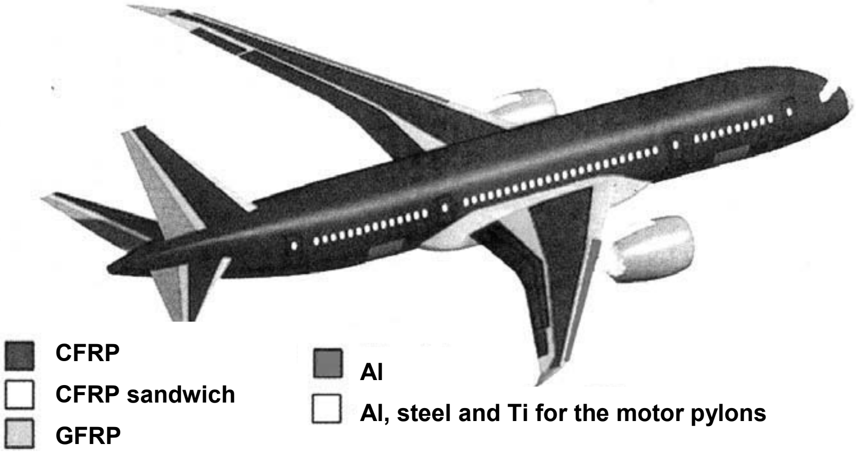

Figure 1.6. *Example of the increasing importance of composites in civil aircraft: the 7E7 Dreamliner has 50% of its structure made of composites. For this aircraft, impact detection monitoring systems are envisaged for outer panels*

As seen above, strong differences exist between structures with SHM and SMS controlling their shape and vibrations. Nevertheless, it is interesting to consider them as part of a whole (see Figure 1.7), since a really smart structure will integrate all three functionalities, and because they all rely on common basic researches aimed at:

– elaborating new sensitive materials to make sensors and actuators,

– developing technologies to miniaturize sensors and actuators, and to embed them without degradation of the host structures,

– conceiving systems for data reduction and diagnostic formulation.

This is the reason why, until recently, works on SHM were often presented at conferences and in journals devoted to the general topic of SMS.

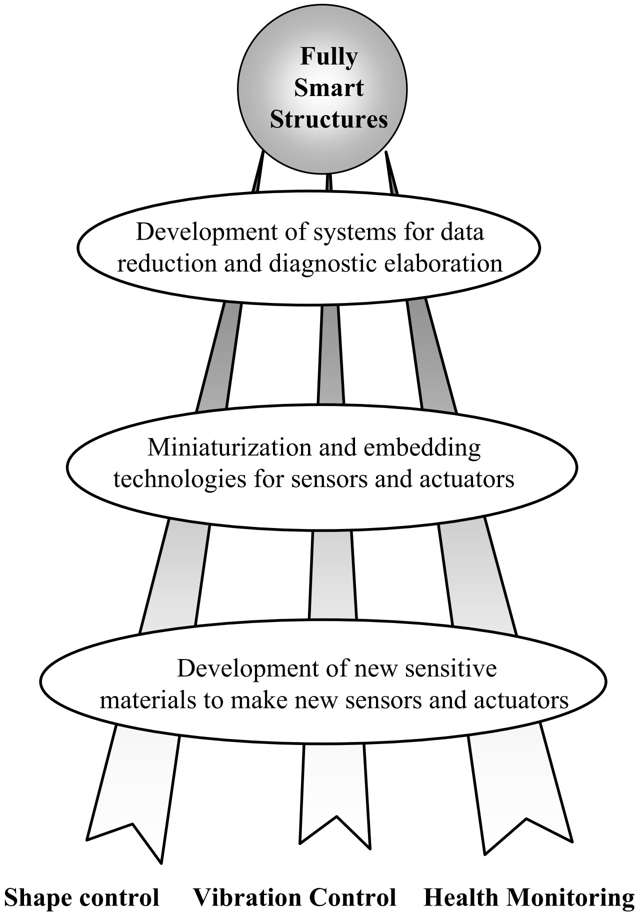

Figure 1.7. *Common basis and complementarity of SHM, shape control and vibration control*

1.4. SHM and biomimetics

The research on SMS in general, and on SHM in particular, is more or less influenced by biomimetics (or bio inspiration). This attitude is a real source of innovation.

Regarding SHM, a strong similarity exists between it and medical activity. This has been well pinpointed in [GAN 92] where a parallelism, given in Table 1.2, is drawn.

Very often, sensitive structures equipped with various types of sensors are compared to living skin. This analogy remains superficial because skin is really an auto-adaptive smart structure controlling its integrity. This is possible thanks to the presence of actuators that can counterbalance environmental aggressions. At the micro scale, the number and variety of skin sensors (see Figure 1.8) is way beyond what is possible with man-made sensitive structures (in one human hand there are more than *100,000 sensors!).* Finally, the reconstruction ability of living tissues is certainly the most difficult function to reproduce.

Phase of life	Man	Structures
Birth	Birth monitoring	Process monitoring
Sound life	Health check-up	Health and usage monitoring
Illness and death	Clinical monitoring	Health (damage) monitoring

Table 1.2. *Parallelism between medical activities and SHM, from [GAN 92]*

Often, another analogy is also used, such as in [BER 03], between the nervous system of living beings and structures instrumented by sensors and equipped with a central processor (see Figure 1.9). The gap between living systems and artefacts is perhaps smaller in this case and study of the functioning of the nervous system and the brain is useful when conceiving control systems (adaptive control influenced by the environment). After detection of the damage by the sensors embedded in the structure, the central processor can build a diagnosis and a prognosis and decide of the actions to undertake (restriction of the operational domain to avoid overloading in the damaged area, and/or scheduling a condition-based inspection possibly followed by a repair).

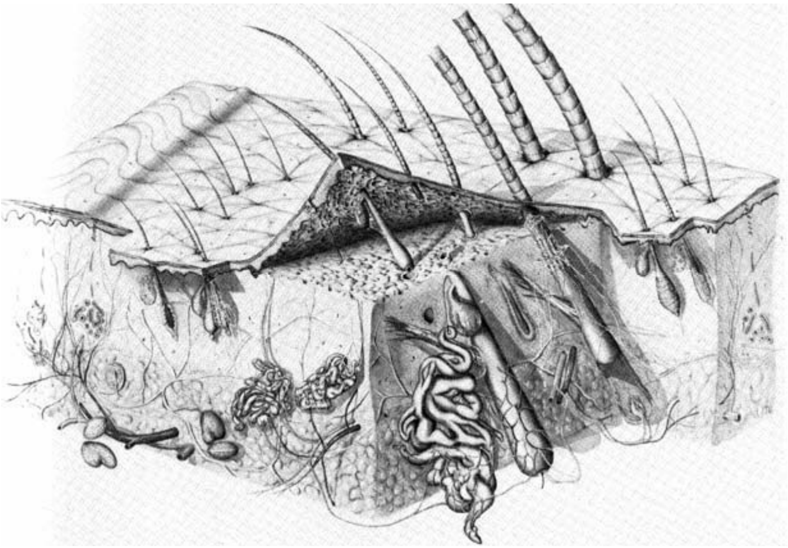

Figure 1.8. *Sketch of human skin showing the variety of sensors and actuators making it a really smart structure, taken from [MON 74]*

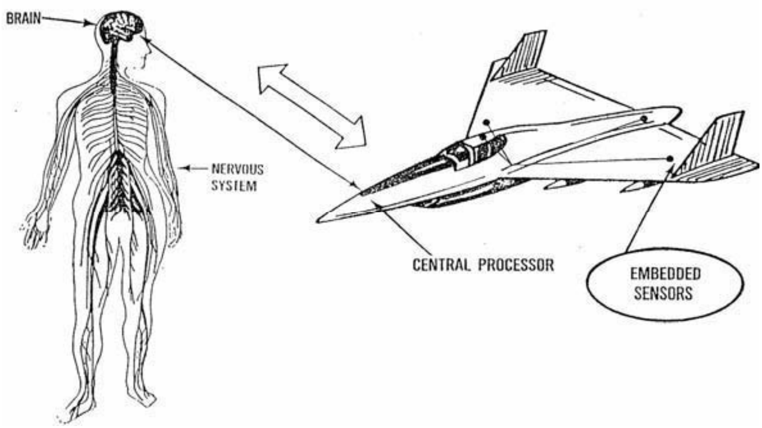

Figure 1.9. *Analogy between the nervous system of man and a structure with SHM, from [ROG 93]*

Biomimetics can help in finding new ideas, but we must avoid trying to copy nature as closely as possible, since we do not use the same materials or the same fabrication processes. For example, bio-inspiration had a strong influence on the strategy adopted by many researchers of supposing that it is mandatory to embed the sensors inside the materials of the structure. Such a choice is important since it has huge consequences for the development of practical systems. The fully embedded solution considerably complicates the technology needed, creating problems of different kinds: higher miniaturization is needed, demonstration of the innocuousness of the embedded sensor for the host structure has to be demonstrated, connectivities complicate the structure design and process, repair ability is problematic, redundancy of sensor networks is needed, the operational life of sensors must be at least as long as that of the structure, etc. The necessity for embedding the sensors is not obvious in most cases, and the drawbacks of surface-mounted sensors are often less critical than those of the more sophisticated solution. In such a case, this particular bio-inspiration could be a false “good idea”.

1.5. Process and pre-usage monitoring as a part of SHM

Sensors for Health Monitoring can be incorporated into the components during the manufacturing process of the composite. Thus, in a global approach including the processing stage, the sensors can be used first of all to monitor the processing parameters in order to optimize the initial properties of the material. The physical parameters of the material that can be monitored during the process are varied: refractive index, visco-elastic properties, conductivity, etc. A range of techniques is available allowing their on-line monitoring: electrical techniques [KRA 91, PIC 99], electro-mechanical impedance techniques using embedded piezo-patches [JAY 97, GIU 03], acousto-ultrasonics (or optical techniques using fiber-optic sensors [CHA 01, DEG 02a]). It could be interesting to mix such different sensors achieving a multidetection [CHA 00].

For temperature during the process and inside the composite, once again various optical fiber-based sensor systems are available. These are predominantly based on fluorescence decay measurements [LIU 00], fiber Bragg gratings [LIU 98, DEW 99] or modified extrinsic fiber Fabry–Perot sensors [DEG 02b].

There is an intermediate phase of the life of a structure that can need SHM too: between the end of the manufacturing process and the beginning of the functioning phase, for certain structures, a lot of handling and transportation operations take place. During this phase, which could be called the pre-usage phase of the structure, accidental loads, not known by the end-user, may occur and threaten the structure’s reliability. A good illustration of such a risk is given in [GUN 99]. On January 17, 1997, the Delta II mission 241 failed when the rocket exploded after a flight of 12.5

seconds, with the consequence that the first of the new set of Global Positioning Satellites (GPS) was lost– see Figure 1.10. The occurrence of damage, caused by a handling overload while the rocket was being transported by road before firing, was strongly suspected. The remedy consisted of equipping the structure with an SHM system that registered the shocks occurring during the full pre-usage phase.

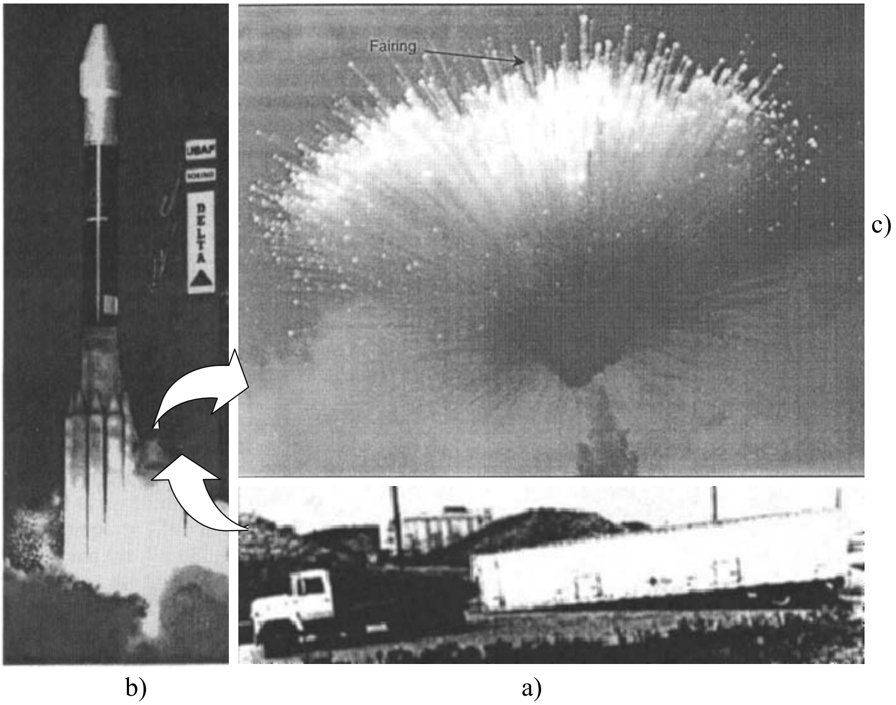

Figure 1.10. *Delta II mission 241 explosion, from [GUN 99], a catastrophic failure which could have been avoided by pre-usage health monitoring – a) road transportation: the rocket is inside the trailer, here detached; b) Delta II liftoff; c) the explosion, initiated from a crack in one of the graphite epoxy motors situated at the base of the rocket*

For this type of SHM, it is easier to detect the possible damaging events than the damage that is thought to have been caused. The sensors can be resistive strain gauges or strain-sensitive fiber-optic sensors for the quasi-static loads and acoustic emission sensors for impact type loads.

1.6. SHM as a part of system management

Health Management can be defined as the process of making appropriate decisions/recommendations about operation, mission and maintenance actions, based on the health assessment data gathered by Health Monitoring Systems [REN 02].

Figure 1.11 presents the general organization of SHM, and how it is included into a Health Management System. This general presentation is independent of the considered application domain. In the present section, more details are given on the different elements of Health Management and the information fluxes. Although this is done by taking the aircraft customer domain as an example – based on a keynote lecture by R. Ikegami from the Boeing Company [IKE 99] – it is representative of the way that SHM can be integrated in more general Health Management systems, whatever the application domain. Structural usage and damage parameters are registered by sensors and used by on-board data acquisition and signal processing equipment. The data from the sensors are transformed into information, related to the structural usage, the environmental history and the resulting damage, thanks to a usage and damage Monitoring Reasoner, which contains information processing algorithms. Predictive Diagnostic Models and Prognostics Models feed a Life Management Reasoner, which converts the information delivered by the Usage/Damage Monitoring Reasoner into knowledge about the structural health of the aircraft. This knowledge is then communicated to an Integrated Vehicle Health Management (IVHM) system, which disseminates the information to the flight crew, the operations and maintenance services, the Regulatory Agencies and the Original Equipment Manufacturer. Thus, a condition-based approach to aircraft inspection and maintenance is possible.

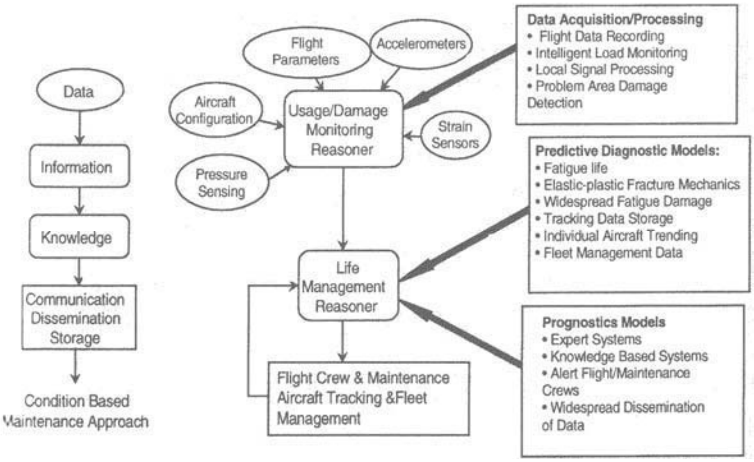

Figure 1.11. *Aircraft Structural Health Management system architecture, from [IKE 99]*

This approach has been refined in more recent papers. In particular, another person from the same company [GOG 03] gives a more comprehensive view of the interconnections between the various reasoners involved in the Structural Health Management architecture. In addition, a description of an IVHM system for air vehicles for the US Department of Defense (DoD) is given by Derriso [DER 03].

1.7. Passive and active SHM

SHM, like Non-Destructive Evaluation (NDE), can be passive or active. Figure 1.12 presents the possible situations in which both experimenter and examined structure are involved. The structure is equipped with sensors and interacts with the surrounding environment, in such a way that its state and its physical parameters are evolving.

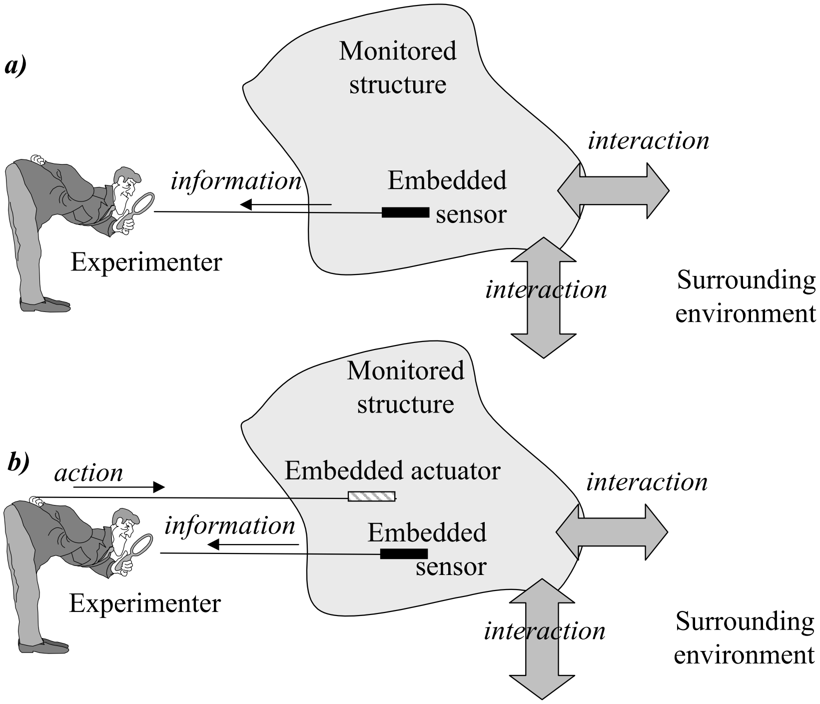

Figure 1.12. *The two possible attitudes of the experimenter defining: a) passive and b) active monitoring*

If the experimenter is just monitoring this evolution thanks to the embedded sensors, we can call his action “passive monitoring”. For SHM, this sort of situation is encountered with acoustic emission techniques detecting, for example, the progression of damage in a loaded structure or the occurrence of a damaging impact [DUP 99, STA 99].

If the experimenter has equipped the structure with both sensors and actuators, he or she can generate perturbations in the structure, thanks to actuators, and then, use sensors to monitor the response of the structure. In such a case, the action of the experimenter is “active monitoring”. In the aforementioned example, the monitoring becomes active, by adding to the first piezoelectric patch, which is used as an acoustic emission detector, a second patch, which is used as an emitter of ultrasonic waves. The receiver, here, is registering signals, resulting from the interaction of these waves with a possible damage site, allowing its detection [WAN 99, LEM 00 b, PAG 02].

In classical NDE, the excitation is, generally, achieved using a device external to the examined structure, but the philosophy is the same. In SHM, the actuator and the sensor can be different or identical in nature, for instance, excitation by a piezoelectric patch and detection of the waves, by a fiber-optic sensor [LIN 02] or another piezoelectric patch. In the case of piezoelectric transducers, it is worth noting that the same device can work as both emitter and receiver, which gives flexibility to the monitoring system, by alternating their roles. This is illustrated in Figure 1.13. With piezoelectric patches, a unique transducer can even perform the two functions at the same time, as in the electromechanical impedance technique [BOI 02, GIU 03].

1.8. NDE, SHM and NDECS

SHM was born from the conjunction of several techniques and has a common basis with NDE. This is illustrated in Figure 1.14, which is taken from [CHA 99]. In fact, several NDE techniques can be converted into SHM techniques, by integrating sensors and actuators inside the monitored structure, as in Figure 1.12b). For instance, traditional ultrasonic testing can be easily converted in an acousto-ultrasonic SHM system, using embedded or surface-mounted piezoelectric patches.

An intermediate solution can be found by only embedding the emitter or the receiver, the other part of the system being kept outside the structure. Figure 1.15, taken from [WAL 99], illustrates this concept. The author calls it Non-Destructive Evaluation Ready Material (NDERM) concept. Perhaps a better denomination might be NDE Ready Structure (NDERS) or NDE Cooperative Structure (NDECS).