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Introduction

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1.1 Introduction

It is widely accepted that maintenance of engineering structures is important to ensure structural integrity and safety. This is particularly relevant to civil engineering and transportation. Aerospace structures for example are inspected regularly. Airframes are monitored for possible fatigue cracks.

A variety of different Nondestructive Testing and Evaluation (NDT/E) methods have been developed for damage detection. Ultrasonic inspection and eddy current technique are good examples of mature, well-established technologies that are widely used for crack detection. NDT/E techniques are often limited to single-point measurements and require scanning when large areas need to be monitored.

In recent years there have been a range of new damage detection techniques and sensing technologies. These methods allow for global, online monitoring of large structures and fall into the area of Structural Health Monitoring (SHM). They are capable of achieving continuous monitoring for damage involving the application of new sensors. Damage monitoring systems, which often use advanced sensor technologies, are concerned with a new design philosophy. Actuators, sensors, and signal processing are integrated to offer progress in this area.

SHM involves integrating sensors and actuators, possibly smart materials, data transmission and computational power within a structure in order to detect, localize, assess and predict damage which can be a cause of structure malfunction now or in the future (Adams 2007; Balageas *et al.* 2006). A typical SHM system is associated with an online global damage

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identification in structures; such systems are most often applied in aerospace (Staszewski *et al.* 2004) and civil engineering (Wenzel 2005).

Although SHM systems utilize NDT/E methods as tools there are many differences in SHM and NDT/E operation principles. NDT/E techniques are commonly applied offline and locally in regions of expected damage while SHM methods should provide real time monitoring of a whole structure during its operation. SHM is a successive step in the evolution of structure diagnostics, which historically evolved from the damage detection concept implemented in the form of condition monitoring (CM) systems. CM systems should be capable of detecting damage based on a global assessment of technical structures during their operation. SHM is expected to go further by the ability of detecting damages in early stages of their development or, in an ideal case, of predicting their occurrence before they really take place (Inman *et al.* 2005).

1.2 Structural Damage and Structural Damage Detection

There are many different connotations of the term *damage* in mechanical structures which in the area of SHM damage can be understood intuitively as an imperfection, defect or failing which impairs functional and working conditions of engineering structures. A more precise definition of damage can be offered when system analysis is used. Structures can be modelled as systems with input excitations and output measurable signals. In this context damage can be considered as an additional excitation that results in energy flow and transformation, leading to modifications of output signals. Therefore damage detection is an inverse problem; measurable outputs are used to detect damage. Damage can also be regarded as a modification to material properties and/or structural physical parameters. These properties and parameters can be modified due to sedimentation and plasticity of material or fatigue and corrosion. In this context damage detection is an identification problem. Material properties and physical parameters need to be extracted to assess damage.

Many different damage detection methods have been developed in the last few decades. Altogether these methods can be classified into model based and signal based approaches. Vibration based methods often utilize physical and/or modal parameters, obtained from physical models, for damage detection. Models are also essential when loads are monitored to obtain information about structural usage. Signal based methods rely on various types of direct measurements such as noise, vibration, ultrasound or temperature.

Both, i.e. model and signal based, approaches require signal processing techniques; the former to develop appropriate models and to analyse changes in these models that are relevant to damage; and the latter to extract features and establish a relationship between these features and possible damage.

The majority of signal based methods rely on a relationship between structural condition and signal features or symptoms. This condition – symptom relationship is often not easy to analyse due to the complexity of engineering structures, sophistication of design and use of advanced materials. Different signal processing methods need to be used for the analysis. This includes signature and advanced signature analysis. The former is based on simple features such as statistical spectral moments or physical/modal parameters. The

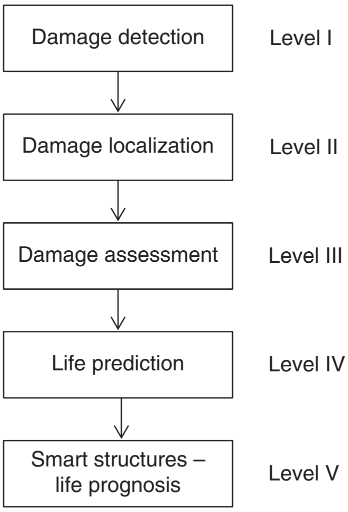

Figure 1.1 Main levels of SHM procedure

latter uses multidimensional features (e.g. vectors, matrices, images) such as spectra, signal instantaneous characteristics or time – frequency distributions.

In this context, damage detection can be regarded as a problem of pattern recognition. Pattern recognition requires feature selection procedures for training and is usually based on statistical, syntactic or neural approaches. Many recent studies in this area are based on new developments related to signal processing (Staszewski and Worden 2009) and machine learning (Worden *et al.* 2011). It is clear that these developments are essential for implementation of any SHM system.

Damage detection forms the primary objective of the overall problem of damage identification. SHM systems' tasks can be classified as a process consisting of five activities that form five important elements or levels (Balageas *et al.* 2006; Cempel 1991; Rytter 1993), as shown in Figure 1.1.

These are: I, damage detection; II, damage localization; III, assessment of damage size; IV, remaining life prediction; and V, smart structures with self-evaluating, self-healing or control capabilities. In this context detection gives a qualitative indication that damage might be present, localization gives information about the probable position of damage, assessment estimates its severity by providing information about damage type and size and finally, prognosis estimates the residual structural life and predicts possible breakdown or failure. The first three levels (i.e. detection, localization and assessment) are mostly related to system identification, modelling and signal processing aspects. The level of prognosis falls into the field of fatigue analysis, fracture mechanics, design assessment, reliability and statistical analysis. This level is very intensively investigated in many laboratories but there are currently no commercially available solutions. All these levels require various elements of data, signal and/or information processing.

1.3 SHM as an Evolutionary Step of NDT

Damage detection/monitoring, NDT/E and SHM are often misunderstood as synonyms and may have the same meaning in many engineering areas. Damage, health and monitoring of structures can be described using various definitions. In general, health is the ability to function/perform and maintain structural integrity throughout the entire lifetime of the structure; monitoring is the process of diagnosis and prognosis and damage is a material, structural or functional failure. Also, in this context, structural integrity is the boundary condition between safety and failure of engineering components and structures. In aircraft maintenance, damage detection and direct monitoring of damage accumulation offers an alternative approach to loads monitoring.

Recent developments in SHM are related either to modifications of well-established techniques, new equipment and sensor technologies or new monitoring principles. This can be illustrated using three examples. First, Acoustic Emission (AE) is a well-established NDT technique used for damage detection for many years. However, when optical fibre sensors – that can be integrated with monitoring structures – are used, AE (passive NDT approach) can be combined with Lamb wave based damage detection (active SHM approach). Secondly, the first NDT/E application of Lamb waves goes back to the 1950s although significant progress was achieved when low profile, smart transducers (e.g. piezoceramic, polymer, discs, paints, fibres) were introduced in the early 1990s allowing a real SHM approach. Thirdly, new damage detection methods based on a nonclassical approach to nonlinear acoustics have been proposed recently offering good damage detection sensitivity.

NDT techniques are often limited to single point measurements and require scanning when large areas need to be monitored. There have been a range of new damage detection techniques and sensing technologies in recent years. SHM methods allow for global, online monitoring of large structures and also offer damage localization. These methods are capable of achieving continuous monitoring for damage with the application of new sensors. Damage monitoring systems that use smart sensor technologies are concerned with a design philosophy directed to the integration of actuators, sensors, and signal processing. There has been an enormous research effort in this area in the last 20–30 years.

SHM, damage detection/monitoring and NDT are often used replaceably to describe the process of nondestructively evaluating structural condition. However, only SHM defines the entire process of implementing a strategy that includes five important identification elements (or levels), as discussed above. What distinguishes SHM from NDT is the global and online implementation of various damage detection technologies which require periodically spaced measurements (or observations), as accurately pointed out in Adams (2007). This process of online implementation needs more advanced signal processing for reliable damage detection than classical NDT techniques.

NDT involves comparing the known input of a measured signal with a known model – it does not require sacrificing the physical system, as disassembly or failure testing would. NDT is usually carried out offline in a local manner, after the damage has been located, or periodically, to improve performance of a structure. NDT techniques are mainly used to characterize damages and assess their severity, if their location is known.

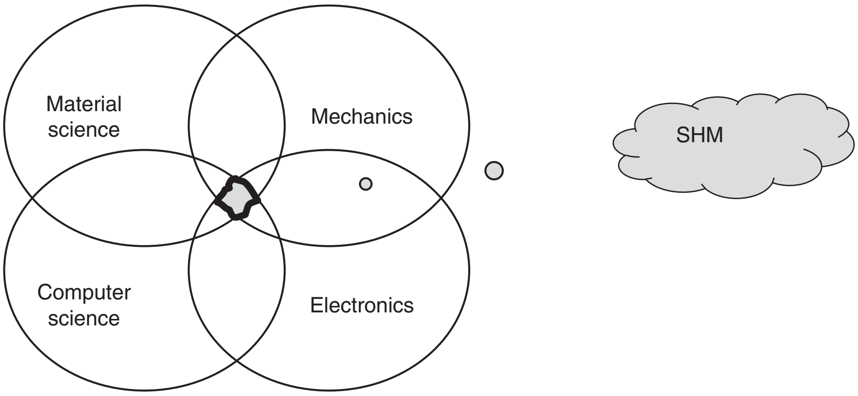

Figure 1.2 Interdisciplinary nature of SHM

1.4 Interdisciplinary Nature of SHM

SHM is an interdisciplinary area of research that integrates such basic sciences as materials science, mechanics, electronics and computer science, and which is strongly related to structures and their life cycle. This is illustrated schematically in Figure 1.2.

SHM approaches require three important elements for damage detection implementation. These are: (1) knowledge of monitored structures and possible damage scenarios; (2) sensors and instrumentation used to obtain signals/data that can be used for damage detection; and (3) relevant analysis which can extract information about possible damage and overall structural integrity. Modelling, numerical simulations and signal processing are important activities of all these three elements.

The interdisciplinary nature of SHM requires a dedicated approach during design, manufacturing and operation, therefore SHM systems are mostly installed on new structures and rarely on old ones that have been operating for a long time. Installation of SHM systems on structures with unknown history of operation is very difficult and the probability of correct damage assessment is much lower than for the new structures.

The design of an SHM system depends on the type of damages which can occur, type of materials applied for the design and physical phenomena employed for damage detection. The complexity of an SHM system design depends on the local nature of material damages that are most likely to occur in the assessed structure and that may not significantly influence the structure’s response measured normally during its operation, e.g. its low frequency vibration spectrum.

Another factor that makes SHM data from a damaged structure difficult to acquire is limited accessibility of its particular components during operation. This often requires an in-depth study of local structure behaviour with the application of analytical and simulation tools that are widely used for understanding damaged structure behaviour and characteristics of the related signals. Due to the relatively high cost of an SHM system implementation of a very careful design and optimization process is recommended, taking into account minimization of the influence of the system on the structure’s performance, minimization of the hardware costs (e.g. number of sensors and actuators), and maximization of the correctness of damage detection and assessment.

Nowadays, multi-physics and multiscale simulation are extremely valuable tools in designing SHM systems. The design process consists of several steps, the most challenging of which are: (1) selecting a phenomenon which is sensitive enough to the damages that are to be detected; (2) defining the required sensing system with self-validation capability; (3) selecting data acquisition and processing architecture; (4) defining feature extraction and information reduction procedures; (5) formulating and implementing procedure of damage detection; and last but not least, (6) damage localization and its size assessment.

There are no general rules on how to solve all these design and implementation problems for any structure. The design methods are dedicated to a given structure, used materials and chosen physical phenomena employed for health monitoring. SHM technology helps to achieve better operational safety and has an economic impact on decreasing maintenance and operating costs because it allows the prediction of possible damage a long time before its appearance and, consequently, gives operators enough time to plan a proactive service and maintenance action.

There are several disciplines that are very closely related to SHM:

- CM – condition monitoring (Inman *et al.* 2005);
- NDT/E – Nondestructive Testing/Evaluation (Staszewski *et al.* 2004);
- SPC – statistical process control (Inman *et al.* 2005);
- DP – damage prognosis (Inman *et al.* 2005);
- MP – Maintenance Planning (Pietrzyk and Uhl 2005), for instance, RCM (Reliability Centred Maintenance).

CM is in many aspects very similar to SHM but in practical use it is dedicated to rotating and reciprocating machinery. The main features of the CM approach are: damage localization is approximately known as well as the type of damage – the number of possible damages is limited, databases with damage symptoms are available, the influence of environmental conditions on the measurement results is very slight, and the economic benefits from employment of CM procedures are well defined. An essential advantage of CM over SHM methods is the well defined economic benefits from the use of CM procedures as well as the fact that many standards used worldwide require the monitoring of rotating machinery.

On the other hand, SHM also has disadvantages: localization of damage is not known, there are difficulties in measurements, due to the limited admittance to the monitored structural components, the type of damage is often difficult to identify, the influence of environmental conditions on measurement results is significant, and the cost of SHM systems is relatively high, which is the reason for their application only on critical structures.

CM systems rely on measurements of structural responses during operation, but they do not use dedicated actuators to excite or trigger effects which can help to detect damage. The differences between CM, NDT and SHM systems in terms of integration of hardware with a structure are illustrated in Figure 1.3.

The main difference between NDT and SHM systems can be noticed in the hardware architecture. In the case of a SHM system, sensors and actuators are built into (or integrated with) the structure, while NDT is an external system with an independent (not integrated with the structure) set of sensors and actuators [cf. Figure 1.3(c)]. Integration of SHM and NDT systems with the other tools is shown schematically in Figure 1.4.

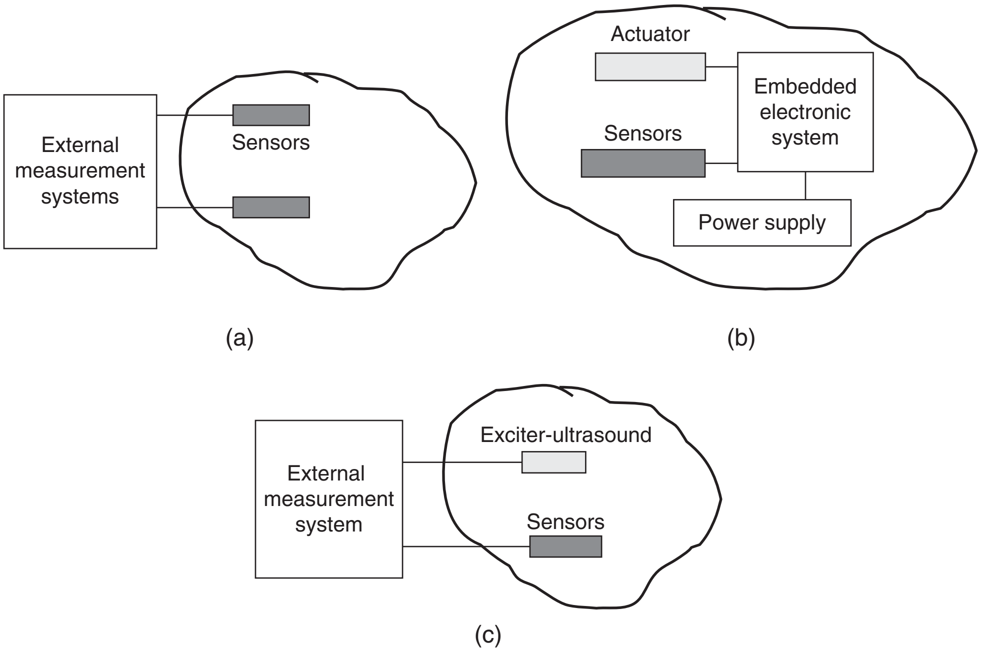

Figure 1.3 Schematic diagram of a typical (a) CM system, (b) SHM system and (c) NDT system

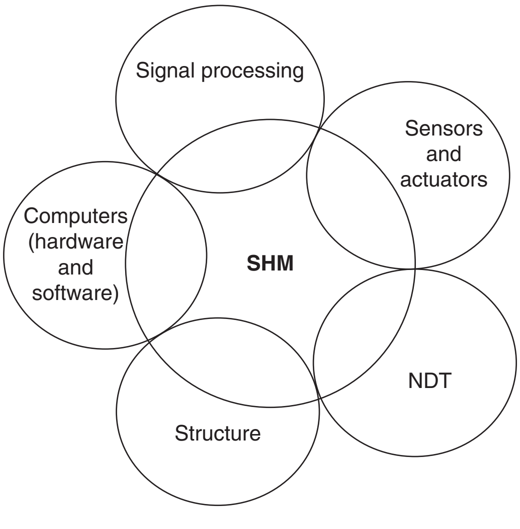

Figure 1.4 Main components of an SHM system

The main difference between NDT/E and SHM is their implementation – NDT/E techniques are implemented offline while SHM ones are implemented online, which makes SHM tasks much more complex than the autonomous NDT/E applications.

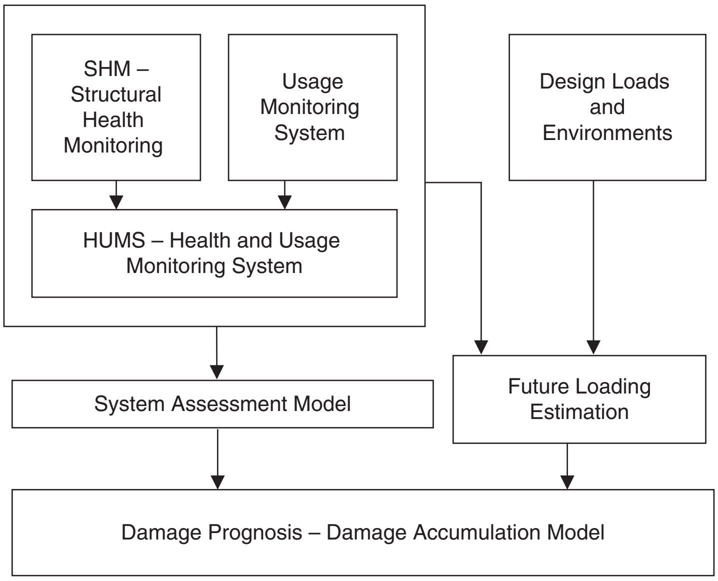

Figure 1.5 Schematic diagram of a typical DP procedure. Adapted from Inman D, Farrar C, Lopes V and Steffen J. *Damage Prognosis for Aerospace, Civil and Mechanical Systems*, © 2005 John Wiley and Sons Ltd.

SPC has similar aims to SHM but the final aim of SPC systems is not only detecting structural damages but process diagnostics – they use a variety of sensors to monitor changes in the process parameters. The process parameters can change due to structural failure and in this respect SHM and SPC are comparable.

DP is used to predict the remaining lifetime of operating structures during which their performance will remain above a given threshold. DP systems use the knowledge about damage size and location as well as expected operational loads. The remaining life prediction is based on a predictive model that acquires information from a usage monitoring system (the system that monitors loading cycle during the structure's operation), the SHM system as well as the past, current and future environmental conditions and expected load levels.

Today's DP systems give only a very rough estimation of remaining life prognosis, owing to the very complex physics of structure destruction if material level is to be considered. Multiscale simulation including molecular dynamics (Packo and Uhl 2011) methods can be helpful to solve this problem in the future. Chapter 2 contains recent results concerning modern numerical simulation methods.

The interaction between different types of monitoring systems in DP is shown diagrammatically in Figure 1.5 (Farrar *et al.* 2005). The most general is the MP system which defines requirements and tasks that are to be accomplished for achieving, restoring and maintaining the operational capability for the whole life of a structure.

MP systems use data from the installed SHM system but also help to analyse historical data in order to detect events that could have been the reason for performance loss. This approach enables preventive service action before damage occurs. Several approaches can be distinguished within this discipline, one of the most useful for mechanical structures is RCM that helps minimize maintenance costs and minimize the risk of structural failure (Pietrzyk and Uhl 2005).

1.5 Structure of SHM Systems

A typical SHM system includes two main parts – a hardware section and an algorithmic section with software. The hardware part includes sensors and optional actuators and the units performing signal conditioning and acquisition, communication, and power supply. These components work autonomously and very often are embedded into the structure. Communication and power supply problems can be often encountered in this type of architecture, which calls for miniaturization of the applied hardware components. The problem with power supply can be solved by energy harvesting units that are currently the subject of many research projects.

Examples of already available technologies are shown in (Priya and Inman 2010). A feasible solution to the miniaturization of SHM hardware is designing and manufacturing MEMS chips dedicated to the SHM purpose, which include sensors, actuators, communication units and processors integrated on board (Staszewski *et al.* 2004). Wireless communication is one of the most commonly used data transfer type in SHM systems, there are dedicated solutions but some of the commercially available, such as zigbee or radio-frequency identification (RFID), can also be applied (Dargie and Poellabauer 2010; Lynch and Loh 2006; Uhl *et al.* 2007).

The software part contains basic procedures for signal processing, signal fusion, hardware control, structure health detection and remaining life prognosis. More advanced systems contain also some procedures related to structural health management.

1.5.1 Local SHM Methods

Modern SHM approaches can be classified into two main groups, the global methods (Adams and Farrar 2002; Doebling *et al.* 1996; Uhl 2004) and local methods (Grimberg *et al.* 2001; Maldague 2007; Raghavan and Cesnik 2007). Local methods monitor a small area of structure surrounding the sensor (sensors) using measurements of a structural response to certain applied excitation. Ultrasonic waves (Raghavan and Cesnik 2007), eddy currents (Grimberg *et al.* 2001), thermal field (Maldague 2007; Uhl *et al.* 2008) and acoustic emission (Pao 1978) are examples of phenomena that are most commonly employed for local SHM. The methods that are most often used for the design of SHM systems are guided waves (GWs; Raghavan and Cesnik 2007), those based on FBG sensors (strain, temperature measurements and ultrasound sensing) (Betz 2003), vibrothermography (Uhl *et al.* 2008) and electromechanical impedance (Bhalla and Soh 2004; Park *et al.* 2003). The state-of-art of the vibrothermography and electromechanical impedance methods can be found, respectively, in Chapters 9 and 6.

There are many other methods that can also be classified as local SHM (Chung 2001) but those methods are mostly used for more specific applications. Classical NDT methods that rely on the characteristics of ultrasound waves propagating in solid bodies can be used in combination with different signal processing and damage imaging techniques.

In the context of SHM, however, the waves are generated by permanently installed actuators that are integrated within a structure. The response is measured by a built-in set of piezoelectric sensors. There are many different techniques employed for excitation and sensing GWs. Recent results in the area of piezoelectric transducers made of macro-fibre composite (MFC) are presented in Chapter 5.

In thin plate-like structures elastic waves can propagate in the form of Lamb waves and the methods making use of these type of GWs are one of the most often proposed local methods in SHM. GW based techniques can be applied for both metallic and composite structures. Generally, local GW based methods require dense sensor networks (to provide a large number of measurement points distributed in space) which generate a large amount of data that have to be processed in order to detect, localize and assess structural damage. The cost of installation of such sensor networks is usually much higher than that for the global methods. Using two-dimensional (2D) phased arrays, capable of electronic beamforming, instead for the dense sensor networks has been proposed as a feasible solution to this problem; details are given in Chapter 7.

Local GW based methods have a number of advantages, the most important is their ability to monitor structural parts without the need for disassembly. Also, since the wavelength of GWs is in the same range as damage dimension they are sensitive to small damages. However, they also have an essential disadvantage – they require dense sensor networks or sophisticated phased arrays that need to be located in proximity to the potential damage, which means that knowledge of the critical damage location (hot spot) is of primary importance. Therefore, local methods are applied when critical structures are to be tested and early phase of damage has to be detected, and the high cost of the SHM system is acceptable.

1.5.2 Global SHM Methods

The global methods are performed if global motion of the structure is induced during its operation (Adams 2007; Balageas *et al.* 2006). Vibration based methods belong to this class. The global methods make use of the fact that local damage, for instance, local stiffness reduction, has an influence on the global structure's behaviour in terms of time and space.

In comparison with local methods, global methods have a number of essential advantages: they can monitor the whole structure using a rough sensor network, sensors do not necessarily have to be located close to damage, and only a limited knowledge about critical location is sufficient. Obviously, global methods also have disadvantages, e.g. the wavelength of the naturally excited vibrations is approximately equal to the dimension of the structure or component and so they have relatively low sensitivity to small damages (especially for lower vibration modes).

Although global methods give only a rough estimation of damage location and size they can be successfully used for damage detection. The most commonly used global methods are vibration based methods (Balageas *et al.* 2006). Low frequency vibrations have been applied for diagnostic purposes for many years (Inman *et al.* 2005; Wenzel 2005). The effects of material defects, supporting structures' failures or geometry defects on vibration response of a structure are well known. The relationship between structural vibration and damages of structures is used in their health assessment.

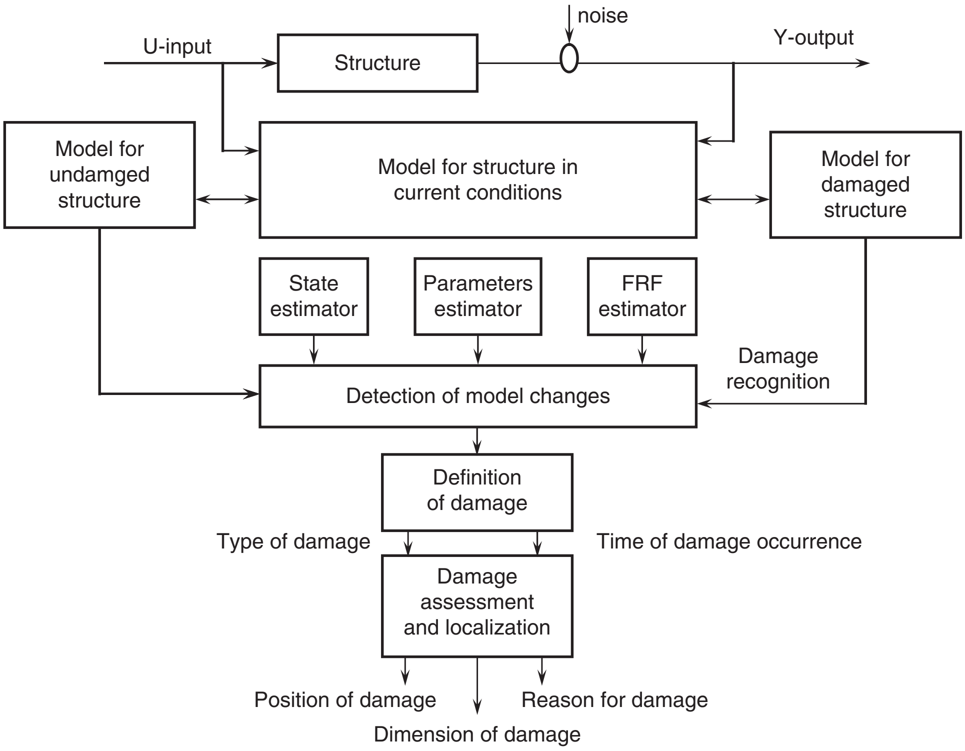

Figure 1.6 Schematic diagram of model based global SHM method

Two types of methods can be distinguished among global methods: signal based (Inman *et al.* 2005) and model based (Natke and Cempel 2000). The signal based methods utilize relations between measured responses of the structure after ambient excitation and possible damages. Signal features in frequency, time and time/frequency domains are the most popular now. The methods are very commonly applied in rotating and reciprocating machinery diagnostics for damage detection, but localization and damage assessment need additional information.

The model based methods employ many different types of models of a monitored structure to detect and localize damage in the structure using relations between the model parameters and particular damages. The idea behind the method is shown in Figure 1.6 (Uhl 2004).

Models of undamaged structure and damaged structure are compared for their parameters or output and differences (residues) are related to given damage and help to localize it. One of the most commonly used models in SHM is a modal model, which can be identified on a real structure with the use of measured external excitation (or vibration excitation caused by operation) and measurements of structural responses at many points.

The modal methods monitor the whole structure by detecting shifts of natural frequencies, increases in damping or changes of vibration modes' shapes. The selected feature should be damage-sensitive. Modal model based techniques can be classified into the following groups (Uhl 2004):

- methods based on perturbation of modal parameters (natural frequency, modal damping);
- methods based on frequency response function (FRF) (stiffness and compliance) variation detection;
- methods based on mode shape analysis;
- methods based on detection of modes' energy;
- methods based on finite element (FE) model updating.

The methods based on modes' shape analysis, such as strain energy analysis or mode shape curvature analysis, are preferred despite the fact that the required SHM system is then more complex than for SHM systems based on natural frequency and modal damping.

The global model based SHM procedures require neither dense sensor network nor sensors located in the vicinity of damage. These methods, however, are less sensitive and have lower spatial resolution compared with the local ones. Their sensitivity and spatial resolution can be improved by a computational model that interprets changes of dynamic properties of a structure.

The global model based methods are employed mainly for the SHM of civil structures. There are several issues that limit the application of these methods, the first is the high cost of a monitoring system caused by very complex cabling. The second is the relatively high influence of environmental conditions on structural dynamic properties, which means that this influence may sometimes dominate in comparison with that caused by serious damage of the structure. The first problem can be solved by a wireless sensor based monitoring system (Uhl *et al.* 2007) and the second one by a special environmental filter which is based on a modal filter [Mendrok and Uhl (2008) and Chapter 8].

Since the global methods are much less sensitive to damage than the local ones, in practical applications, they are used only for damage detection.

1.6 Aspects Related to SHM Systems Design

The entire process of monitoring for possible damage in engineering structures depends on structural design concepts. This can be illustrated using aircraft design. Current design principles of aircraft structures are based on the *safe-life* concept. Load spectra representative of typical operational conditions are first determined. This requires a significant amount of data related to mission profiles, mass distributions and many other parameters. The load spectra and fracture mechanics are then used to evaluate structural components in terms of their service fatigue life. This is followed by a series of fatigue tests of materials, coupons, elements, subcomponents and components, leading finally to the Major Airframe Fatigue Test (MAFT).

In practice, the scatter in design input data (e.g. unknown parameters, change of load conditions, variation of material properties, quality of manufacturing, human errors or structural modifications in service) is quite significant. Therefore various safety factors are imposed on the structure to guarantee the safe fatigue life. The structure is designed for a specific number of flight hours and retired from service afterwards even if no failure occurs.

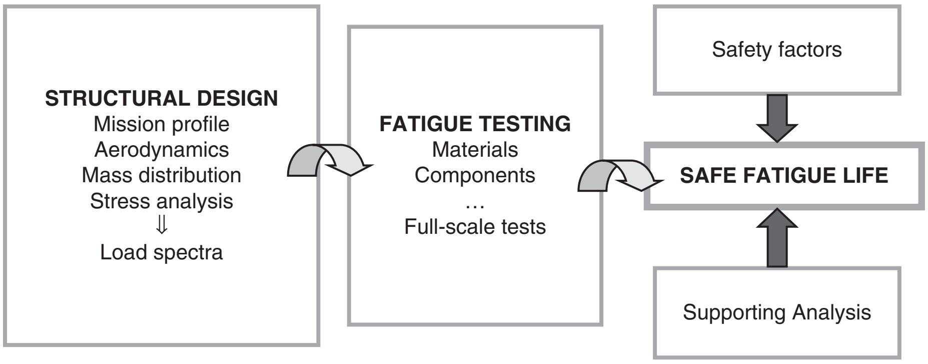

Figure 1.7 Safe-life aircraft design concept

The estimation of operational life of ageing aircraft is even more difficult. The safe-life design concept, illustrated in Figure 1.7, leads in practice to structures that are safe but over-designed. This is not desirable if economy and performance are analysed. Noncritical structural components that are exposed to multiple load paths are often designed using the fail-safe concept. Even if these components develop damage, the structural integrity is not jeopardized due to the assumption that damage can be detected before any catastrophic failure. This requires periodic inspections of components.

Monitoring techniques offering reliable detection, location, estimation of severity and prognosis of damage can lead to the *damage-tolerance* design concept. Detected damage is monitored to maintain the safe life of aircraft in this design concept. Although significant inspection effort is required, this concept can lead to lighter structures and better performance. In fact, the prevention of crack initiation behind the safe-life design concept does not prevent catastrophic failures. Therefore maintenance and inspection of aircraft structures is very important whatever the design concept. It is important to note that fatigue of materials in Aerospace Engineering has significantly contributed to structural design. The *safe-life* and *fail-safe* design concepts, introduced in aerospace, are widely used in many other areas of engineering.

1.6.1 Design Principles

The design of SHM systems requires dedicated procedures and tools because of the costs, the high level of responsibility and the interdisciplinary nature of system design. The procedure for SHM system design consists of the following steps:

1. Assumptions on the type of damage which should be detected.
2. Choice of physical phenomena which is sensitive to damage occurrence.
3. Formulation of monitoring methods – algorithms (for detection, localization and assessment of damage dimension).
4. Simulation study of the method (virtual prototyping).
5. Laboratory validation of the method (physical prototyping).

6. Testing of system performance [probability of detection (POD)].
7. Implementation of SHM system.
8. Operational test of the system.
9. Installation and operation of the system.

A careful description of the structure, environmental conditions and expected load ranges as well as a list of possible damages are necessary to choose appropriate physical phenomena which can be used for structural monitoring. The chosen phenomenon has to be measurable for a particular structure and operation conditions, however, its normal operation should not be disturbed. It is preferred that the phenomenon can be excited by ambient excitation, but in other cases a special actuation system should be designed to excite the structure. The excitation level should be as low as possible because of the limited power supply and high enough to cause measurable responses of the tested structure. While formulating the algorithm for correct damage detection results, the required computational power and volume of data from measurements have to be considered. Minimal computational power and minimization of the amount of required measurement data are important due to the limited availability of power supply and limited memory of the embedded computer power, especially when a wireless embedded SHM system is under design.

The next step in the design procedure is testing the formulated solution by simulation, which requires creating models of the monitored structure, damage scenario, sensors and actuators. The goal of this simulation is to create tools that enable testing of the correctness of the formulated method and choosing a measurement system that will enable measurements of the structural response with sensitivity matched to the monitored damages. Sensitivity analysis of a structure’s response to damage accuracy is a basic tool which helps to design a monitoring system. With the use of the model and its simulation the POD can be tested too (Mendrok and Uhl 2008). For a chosen SHM system, the POD should be as high as possible in order to consider the formulated method as useful in the design of SHM for a given structure. But due to undefined localization of the damage and fixed position of the applied sensors, the model based assessment of POD can be a difficult task [Gallina *et al.* (2011) and Chapter 3].

A much more accurate determination of POD can be done by applying an experimental laboratory test. In such a test damage is defined by a sample with known damage location and dimension and well known properties of a healthy structure. The laboratory test should confirm the sensitivity and probability level of the correct damage detection.

The next step is implementation of the designed SHM system, which requires conformity with related standards that depends on the application area, e.g. aviation standards are completely different from those that have to be obeyed in civil engineering. This is the main reason for completely different designs of SHM systems in both branches.

The modularity of SHM due to the requirement of scalability is an important feature during the implementation phase. In subsequent phases the SHM system is installed on a real structure in the operation environment. The operation test is always required to confirm the correctness of the system design.

A further development of SHM systems requires new automatic algorithms of damage detection, localization and assessment, new state prognosis methods and algorithms, and development of self-diagnosis and self-healing of critical structures.

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