Chapter 1

Structural Health Monitoring: An Overview

This chapter deals with the necessity of health monitoring of structures, focussing on the various components involved in structural health monitoring (SHM). While implementation of the SHM scheme imposes a big challenge in real timescale, the details of various factors that influence the implementation process are also discussed. Several components involved in the SHM process are highlighted, while specific issues with respect to concrete structures are discussed in detail. This chapter also summarises several advantages of SHM along with the long-term and short-term benefits both from economic and safety perspectives.

1.1. Introduction

Civil engineering structures in general and offshore structures in particular attract huge capital investments apart from demanding a longer period of time for their construction, installation and commissioning. Continuous monitoring and proper maintenance of structures are vital requirements of the modern society. It is no longer optional for the owner to upkeep public buildings in terms of its functional maintenance, and legal mandates have also been imposed on the safety and security of public buildings; in this aspect, health monitoring of infrastructure is also supported and funded by government agencies. While advanced methods of analysis and design of structural systems, which are in compliance with the code guidelines, confirm least probability of design failure, construction difficulties pose various challenges, resulting in deviations to the design solutions causing uncertainties. In addition, ageing of structures poses additional challenges in terms of strength degradation and non-availability on demand.

In addition to helping engineers recognise poor structural conditions and other safety issues, advancements in SHM also help professionals determine potential risks of buildings caused due to ageing and other environmental factors. SHM is particularly useful in preventing water and flood damage caused by failed dams, dykes, pipelines, and other similar structures. SHM essentially examines the state of the present condition of structural systems to assess their functional fitness and performance levels. If the condition assessment envisages a poor performance level in comparison to that of the desired ones, repair processes are immediately initiated. It is therefore emphasised here that structural repair is invoked only when the structural system undergoes significant damage; but such practices are not acceptable in the case of structures of strategic importance, such as nuclear power plants, large reservoir dams, offshore and coastal structures. Hence, in order to plan for a schedule of preventive maintenance, both in terms of shutdown time of the facility and economic planning, SHM is used as one of the essential tools in reliability engineering. Further, SHM also enables the reduction of long- and short-term costs with respect to maintenance and repair of public building; this reaps the economic benefit of the construction industry to a great extent.

Large, complex and costly engineering structures are constructed to last for a longer life span. While the usual practice is to design them for maintainable conditions, their design life is usually extended even under non-maintainable conditions. The general scope of structural health monitoring (SHM) includes structural assessment, monitoring and control, which can be abbreviated as SAMCO; all the three components are vital in SHM. Structural assessment involves the assessment of actual conditions and load-carrying capacity of the structural systems. Diagnosis is a vital part of SHM, which involves integration of various sensors used for measurements, computational power and processing ability within the SHM system itself for effective outcome. Structural monitoring deals with the supervision of structures on a continuous basis using sensors or electronic gadgets. They are carried out in order to maintain the functional utility of the structure; to be very precise, it is done to ensure the availability of the system on demand. Thus, it includes both periodic and preventive maintenance. Structural control deals with the control of the dynamic response behaviour of structures under various environmental loads. This involves the establishment of control mechanisms so that responses are under the preferred limits even on unforeseen increase of load magnitudes. The above three vital components can be prioritised as follows:

- Assessment involves the preparation of existing conditions of structure in terms of its geometric fitness and load capacity and therefore deals with the examination of those conditions of the structure that one can take advantage of beyond its design life.
- Monitoring is more or less related to maintenance, ensuring the availability of the structural system on demand. Monitoring of structures does not necessarily mean knowing the status of structures in real time. Since all structures are designed with a margin of safety, which can be used to exploit its design life to at least a marginal extent, tolerance can be allowed in delaying maintenance. Monitoring, therefore, enables effective planning of maintenance.
- Control aims to reduce or mitigate undesirable (modes of) response even under unforeseen increase in magnitude of loads. This is very vital in the case of offshore compliant structures as their load resistance is often derived from FORM resistance and not from their strength. Excessive displacements in global degrees of freedom, as a rigid body motion, may become undesirable as this may even challenge their hydrodynamic stability. Hence, control of both rotational displacements in particular and translational displacements in general is very important for ensuring structural safety and safe operability.

Priority depends upon two factors: (i) type of the structure and (ii) economic considerations, which drive the whole concept of application of SHM in structural engineering. In view of a normal type of structure under given budgetary normal considerations, assessment of the condition of the structural system is very important. In order to develop an effective design, one can even prescribe control mechanisms; but, prior to that, maintaining the utility value of the structure to ensure its availability is also equally important.

SHM actually deals with the development and implementation of methods and techniques, which are useful for ensuring the availability of the structural system to perform its intended function on demand. Thus, the main objective is neither exercising a control algorithm nor the assessment of load-carrying capacity but ensuring the functional utility value even under critical environmental conditions. Continuous monitoring (or even periodic monitoring to a larger extent) ensures preventive maintenance and helps policy and planning guidelines to ensure the functional value of strategically important structures. For example, a periodic and preventive maintenance of a highway bridge or gas pipeline shall ensure uninterrupted service and minimum downtime, even in the case of any critical repair. Civil engineering professionals agree to the fact that maintenance of infrastructure facilities is vital in order to elevate the standard of the structural systems in terms of their serviceability, appearance and safety. As certain clauses of structures, such as industrial structures, highway and railway bridges, nuclear power plants, offshore structures, naval structures, etc. are vital for the economic growth of the country, ensuring their availability on demand is necessary for the safety and security of public life. They also influence the economic growth of the nation in the international market. Society essentially depends on these structures for various reasons, such as economic, environmental, life-quality updates, safety and employment perspectives. Most of such structures also reach critical age, which can result in strength degradation, degraded quality of appearance, decreased load-carrying capacity and reduction in the overall dependency. In order to ensure and continue a comfortable dependency on these structures, both periodic and preventive maintenance are important. There are three ways by which maintenance can be attempted:

(i) periodic maintenance; (ii) preventive maintenance; and (iii) critical maintenance (maintenance on demand).

Critical maintenance is more alarming and dangerous, where a structure is maintained only after its critical age. In this case, recovery of strength of the structure is very difficult. For example, let us consider offshore structures used for oil and gas exploration and production. An offshore platform working continuously on oil and gas production results in an outcome or commercial benefit, which could be revenue, employment, constant research and development for further exploration and production. If, due to unavoidable reasons, structure needs to be shut down for maintenance, the shutdown period (known as downtime) will primarily lead to loss of revenue, which is not preferred. On the other hand, if a total shutdown could be avoided by way of preventive maintenance, it can lead to several advantages; economic benefit is the foremost one. When the structures reach critical age, there can be strength degradation due to material corrosion in sea. Thus, these structures will not be able to alleviate the encountered lateral loads successfully. It may also result in structural failure, which can cause disaster. One cannot afford to lose such novel, unique and high-investment structures. Preventive maintenance can avoid such catastrophic failures. To carry out preventive maintenance, one must assess the present condition, monitor the condition continuously and then plan the repair procedure even before the structure actually needs it. Instead of doing a periodic maintenance, strategic structures can demand a preventive maintenance. Preventive maintenance is possible only through detailed assessment, monitoring and planning of repair, which are all encompassed under the framework of structural health monitoring. Therefore, one of the most important deliverables and main outcomes of SHM is the avoidance of a premature failure or a breakdown of the facility.

Let us consider another example: a naval dockyard, which is essentially an open channel to house large vessels for their periodic maintenance. Periodic maintenance could be partial or complete weld upgrade, painting, treatment for biofouling, upgrade fault correction for electromechanical systems, etc. Navy operates on various kinds of strategic vessels like submarines, which need to be inspected for periodic maintenance or emergency fault correction; such operations are usually carried out in a dockyard. Dockyards are very few in number and quite expensive. If a dockyard is undergoing periodic maintenance, which demands the shutdown of operation during an emergency requirement of docking a naval vessel, functional assurance of the essential service becomes unguaranteed. Hence, the shutdown time caused by a periodic maintenance schedule on a dockyard deprives the basic utility value of the system itself; this can be avoided if the dockyard undergoes preventive maintenance. Maintenance should be carried out in a preplanned and preventive manner, so that the dockyard always remains functional even during critical environmental conditions. However, utility value can be slightly decreased in terms of its operational capacity, but a complete shutdown of the dockyard can be avoided. Hence, preventive maintenance of essential services is far more advantageous in comparison to periodic maintenance. SHM ensures constant maintenance costs and high degree of reliability of the service instead of high maintenance cost and low degree of reliability.

1.2. SHM Analogy

When a human being falls sick, he is physically examined by a medical doctor. Similarly, inspection demands a complete analysis of the structural condition, which can be done by structural monitoring. Further, in the case of a human being, health can be monitored on a continuous basis through several means under any situation as per the advice of the doctor. In a similar manner, structural health monitored using sensors records the response of the structure through a typical time-history response plot. For example, accelerogram is the graphical output of seismograph. In the case of human health monitoring, when one undergoes electrocardiogram, plots are available, which indicates the health condition of the human being. So far, the person is referred to as human and not patient because he is not sick. This process of health monitoring is called “diagnosis” in medical terms and “monitoring” in SHM.

Monitoring the output could result in the assessment of the condition of the structure and enable one to reach a conclusion about the present condition of the structure; this is called as “assessment”. Similar to the post-diagnosis report, which clarifies the state of health of the human being and helps seek expert medical advice, SHM helps one to recommend certain control algorithms for reducing (or completely mitigating) the undesired responses of the structure; this is termed as “control”. Based on the diagnosis and assessment, the doctor may recommend a surgery, which attempts to mitigate the problem. In short, both human health monitoring and structural health monitoring result in ensuring overall safety and satisfactory functionality of the system (or human) as the case may be; hence, both processes follow the same analogy.

1.3. Necessity for SHM

The overall objective of SHM is to ensure a satisfactory performance of the structural system in its present condition. Infrastructure investment is always not only towards new construction but also includes its maintenance. There can be a slack-down time in infrastructure growth under economic recession during which investment towards maintenance may become important. During such periods, major investment can be directed towards the maintenance of old existing structures. Structures that have reached critical age (may be 30−40 years of service life) demand higher order of maintenance to upkeep their functionality. The deterioration of the structure’s condition depends on various factors: (i) type of material; (ii) nature and type of loading; (iii) environmental conditions; and (iv) degree of maintainability. However, in general practice, structures with 30−40 years of service life fall under the category of critical ageing, which requires adherence to a periodic inspection and a systematic maintenance schedule. The state of health of the structure and the damage are assessed by a few closely related disciplines, which include structural health monitoring (SHM), non-destructive evaluation or testing (NDE or NDT), condition monitoring (CM), health and usage monitoring system (HUMS) and damage prognosis (DP).

SHM involves the implementation of damage detection strategy for structures of high importance. Condition monitoring is similar to that of SHM but commonly used in mechanical and power generation systems. NDT is more a traditional technique, which includes visual inspection, liquid penetration, ultrasonic, X-ray, radiography, eddy current methods, magnetic field methods, etc.

Under the expected rise in the repair and retrofit segment in the near future, construction industries should be prepared with methods, strategies and technological skills to carry out repair. It is possible only when SHM is in existence. SHM is essentially a process of developing and implementing damage identification strategy, which involves the identification of a statistical pattern affecting the present and futuristic conditions of the structure. It is therefore necessary to train the technological manpower, who can take care of immediate repair and retrofit procedures for the structures, which demand this kind of attention. SHM deals with the preparedness of carrying out repair and retrofit of structures that demand special attention. One of the major and successful outcomes of the healthy practice of SHM is disaster prevention. One can completely mitigate disasters caused by natural events if the structures are monitored on a continuous basis. It is also important that they are maintained to upkeep their functional value with respect to their present age and working conditions.

One of the main objectives of SHM is to fulfil the necessity of a disaster prevention mechanism. Natural disasters such as earthquakes, Tsunamis and cyclones have demonstrated the vulnerability of buildings, coastal structures, nuclear reactors and other structures of strategic importance under the unexpected environmental forces. Thus, natural disasters not only lead to loss of life but also challenge the economic sustainability of the nation. Hence, the first necessity is the preparedness for such natural calamities, which is followed by ensuring economic sustainability and knowledge update. For example, recent earthquakes taught interesting lessons of various failure scenarios, so that appropriate design procedures and ductile detailing are enforced through the design codes. This is possible only when there is a constant update about the loss of strength of structural systems under unexpected forces like earthquakes. This is termed as monitoring, which is actually a vital part of SHM.

1.4. Scientific Justification

In the overall domain of SHM, the following steps may be of fundamental interest:

- Identify structures that need monitoring.
- Acquire information about probable degradation of materials and risks involved in the structural system from the designers.
- Establish expected responses of the system to these probable degradations.
- Design a proactive SHM system, which can detect such conditions through a carefully integrated sensor network.
- Install and calibrate the SHM network.
- Acquire, analyse and manage data.
- Schedule a proper emergency response plan in the case of any emergency that arises from non-functional responses of critical infrastructures.

Damage detection during the early stages requires continuous monitoring. SHM encompasses a process of implementing damage identification strategy to the offshore, civil, mechanical or aerospace structures (Farrar and Worden, 2007a–c). It can be either global or local assessment. Global assessment is when the structure is assessed as a whole. Based on the response of the whole structure, the damage and remaining life of the structure are assessed. On the other hand, in local assessment, each member is examined independently and maintenance approach is carried out. SHM, therefore, evolves time-based maintenance approach, which is an important outcome of condition assessment. In time-based maintenance approach, the maintenance process is proposed to be carried out at specific intervals of time, irrespective of the current state of the system. If a member fails in between, then it has to be replaced. Such interventions shall increase the downtime of the system if the repair operation requires sufficiently longer lead time. This type of process includes tradeoff between the cost and the risk, which arises as a consequence of the damage. This shall also account for unexpected variations in load and environmental conditions that prevail on the structure. Most of the private and a few government industries show interest in detecting damages in their developed products and manufacturing infrastructure, so that damages can be detected at the earlier stages of process/production. Such detection requires intensive use of SHM, which is motivated by potential life-safety and economic impact of this technology.

SHM has been successfully deployed in the oil industry, large dams and highway projects, whose installations have been noted with careful attention and appreciation to the research efforts. However, a few of the heritage structures in Italy (see, e.g., Lady of Shrine, Siracusa) are also kept in the loop of SHM network due to their cultural importance. According to the International Society of Structural Health Monitoring and Intelligent Infrastructure (ISHMII), a lot of bridges and structures are monitored using various sensors for any damages; application is quite common and popular in European countries due to the fact that Europeans have a culture of retaining old structures in a good condition. Some Asian countries have also seen a rapid growth in health monitoring culture: Japan, Taiwan, China and Singapore, where monitored structures are quite healthy and safe from the functional perspective.

The use of SHM in assessing occupational safety of buildings under natural calamities like earthquakes is quite vital. For example, as such, there exists no quantifiable method to determine occupational fitness of a residential building after a significant earthquake. SHM can be seen as one of the scientific tools to minimise uncertainty associated with post-earthquake damage assessments. Similarly, a dockyard, after being serviced for a vital repair, needs to be assessed and continuously monitored for the successful recovery of strength and functionality of the dockyard. If SHM methods can assure prompt reoccupation of industrial buildings and critical infrastructure like railway bridges, highway bridges, etc. after significant earthquakes or floods, this can help mitigate economic losses associated with such natural calamities. While it is a fact to understand that most of the current structural and mechanical systems have crossed their design life on a time-based model, buildings of heritage value are overdone for sure. Hence, SHM technology will allow the current time-based maintenance policies to evolve into potentially cost-effective condition-based maintenance policies. But, in condition-based maintenance approach, actual state of the structure is taken into consideration for conducting the maintenance process. Such a process, when implemented, will reduce the downtime. In addition, it increases productivity, reduces life-cycle cost and increases safe operability (Liu and Nayak, 2012). SHM enables preventive maintenance operations when there is a likelihood of response exceeding the threshold value. SHM activities involve a five-level classification as follows (Rytter, 1993), (Keith *et al.*, 2003):

- First level is the assessment of the response to determine whether the structure is damaged or not.
- If damaged, it further tries to identify the localisation of the damage.
- Based on the data, it will quantify the amount of damage.
- It shall also predict future progress of the damage and remaining service life.
- It further recommends appropriate remedial and repair measures to restore both strength and functionality of the structure.

Modern world depends on complex and exhaustive systems of infrastructure. Many structures were constructed during the economic progress in the recent past. All these structures are now aged. According to statistics, in many advanced countries, more than 40% of the bridges are critically aged (found to be older than their design life). In general, the public funds available are too less for the replacement of the structure. It can only enable partial repair of the structures. In such cases, one needs to know the justification for the partial repair, which can be established only through SHM. Using effective approaches, a regular periodic maintenance can also be planned effectively. Thus, effective planning of maintenance also requires a continuous monitoring of the condition, which is an essential outcome of SHM. Therefore, SHM is completely a scientific approach involving the capability to understand the importance of successful maintenance of civil infrastructure. Further, SHM also involves the use of various automated tools and systems, which are used to improve the inspection procedures and techniques of repair. Guniting is one of the methods of repair, which can give surface treatment for material degradation against corrosion. The scientific approach of SHM can improve safety standards of public life. It can reduce risks and enable us to discover new methods of reducing cost of repair and rehabilitation.

Vibration-based damage detection techniques are commonly used in damage diagnosis as they are one of the most efficient methods. There are various physical parameters; microelectromechanical system (MEMS) has its own advantages and is applied in various fields of application, such as biomedical, automotive, construction and consumer sectors. Vibration-based damage detection methods are further classified into traditional and modern approaches. The traditional method is based on the principle that change in mass and stiffness will be reflected in the measurements of natural frequency and mode shapes of the structure. When the measured data of natural frequency or mode shape are different from that of the normal, it indicates the initiation of damage. The modern method involves the online measurement of structural response to detect damage with the help of signal processing techniques, artificial intelligence and neural networks (see Table 1.1). Dynamic response of the structure under different loads is measured online while SHM

Table 1.1. Sensors for vibration monitoring.

Physical parameter	Sensing principle	Technology
Acceleration	Inductive sensors	Conventional
Velocity	Capacitive sensors	MEMS
Displacement	Piezoelectric sensors	
Magnetic field	—	Giant magneto-resistance
Magnetic resistivity		
Optical property	Photoelectric sensor	Fibre Bragg grating
	Optical fibre sensor	Fabry–Perot interferometer
		Intensity sensor
Acoustics	—	Ultrasonic probes

indicates change of structural parameters, thereby detecting damage in the structure.

1.5. Major Advantages

SHM possesses several challenges, the foremost challenge being optimal definition of sensors in terms of its choice, type, layout and number of sensors to be deployed. The next challenge comes from the communication systems whether these sensors will be wired or wireless, whether the communication will be through R/F or other modes of transformation. There are some salient advantages of deploying the SHM scheme. These advantages are common to a variety of structures, such as civil engineering structures, mechanical systems, offshore structures, naval systems, aviation systems and nuclear reactors. The advantages are listed as follows:

(1) The major advantage, which is mostly welcomed by the engineering fraternity, is that the SHM scheme enables one to update the integrity of the structure. This is true if monitoring is carried out on a continuous basis.
(2) The utility value or functional value of the structure is enhanced. It means the structure is put to its optimal use.
(3) It minimises the downtime. A preventive maintenance can be preplanned ahead based on the monitoring and assessment of the structure. This is very helpful in naval defence systems.
(4) Public safety is enhanced. For example, if SHM is deployed on a bridge and monitored continuously, then its functional ability is predicted or assessed to a higher accuracy to avoid any catastrophic failure.
(5) There is a significant improvement in maintenance organisation of public structures. One can avoid unnecessary maintenance schedule. Critical elements which require immediate attention are not ignored under SHM deployment. It enables one to carry out periodic maintenance with performance-based focus. This a very recent trend which enables a lot of cost-saving and enables an engineering efficiency in preplanning maintenance in terms of structures of very high strategic importance.

(6) It reduces investment on maintenance labour. Inspection labour is expensive, it is also very special and technical, and it is time consuming. All these can be avoided by the regular maintenance schedule. SHM reduces human involvement towards inspection, planning and decision making on maintenance schedule. Maintenance is actually planned, scheduled based on the structural condition automatically. Unsatisfactory maintenance has many critical disadvantages. The consequences that arise from unsatisfactory or improper maintenance cause further disaster, e.g., the accident of Aloha airlines and the collapse of the Mianus river bridge. Efficient use of funds towards maintenance is reduced and time or schedule of maintenance can result in downtime of the facility despite its critical need, e.g., dockyards.

One of the major advantages of using SHM is that it includes the reduction of cost related to inspection and mitigation of impact of structural disasters caused by nature. Further, it reduces the need for immediate repairs and thereby improves public safety. From an overall perspective, it improves cost efficiency of public funding in a more reasonable manner, as discussed in the following sections.

1.5.1. *Increased safety*

SHM practices ensure improvement in public safety. SHM also ensures effective utilisation of public funding towards the maintenance of civil infrastructure of any nation. SHM is also advantageous in the replacement of water supply pipelines which had severe metallic corrosion. Preventive maintenance in this case enhances the quality of public life. It ensures the use of new tools and technologies to carry out and maintain serviceability of structures and also helps us to even declare them as safe or unsafe. In the case of ageing structures, SHM is advantageous because the health of the structure can be monitored using sensors, data collection and analysis to initiate a preventive maintenance. Further, continuous monitoring and analysis of the recorded data helps to update design procedures by resolving any flaws in the design. It also serves as a knowledge update on the design of structures.

1.5.2. *Detection of early risk*

SHM tools can be deployed to detect a poor structure or its condition, and therefore its usage can be limited. This enhances public safety. Secondly, SHM can be seen as a highly useful tool in preventing water and flood damage caused by failure of big reservoirs. In such cases, built-in sensors will be useful to monitor the change in water level which can be used to detect minor leaks and major failures as well. SHM can also be used as a new design tool in the case of design of foundations for bridges, pavements, etc. To a reasonable extent, ground movement can be monitored, which can help us in predicting earthquakes. This will improve the preparedness of the structures during the forthcoming earthquakes.

1.5.3. *Longer life span*

Both preventive and periodic maintenance enhance the service life of the civil structural systems. Continuous monitoring improves the plan for preventive and repair procedures. Most importantly, it accounts for human errors if made. SHM can also improve the existing design methods by eliminating the flaws in the design procedure. This enhances immediate safety in public buildings.

1.5.4. *Cost efficiency*

SHM can be helpful in the effective utilisation of public funding towards maintenance. It can essentially avoid unwanted maintenance of structures with good health, i.e., an unnecessary periodic maintenance of a system already in good health can be avoided. It avoids shutdown of operations as explained earlier, which can enhance the economic efficiency of the system by enhancing the return on investment (ROI) in the case of oil and gas industry.

1.6. Components of SHM

SHM deals with continuous monitoring, assessment and then control algorithm to be in place for establishing a satisfactory performance level of a given structural system or any infrastructure. Considering this as one of the important objectives of SHM, let us look at the components involved in SHM. The components of the SHM process consists of different stages: (i) operational evaluation; (ii) data acquisition (DAQ), fusion and cleansing; (iii) feature extraction and information condensation; and (iv) statistics-based model development for feature identification. Operational evaluation is focussed on a few vital points: (i) damage definition, i.e., under what condition, it is said to be damaged; (ii) economic issues; (iii) data management; and (iv) environmental or operational constraints, if any. Data acquisition, fusion and cleansing stages deal with the sensing and data acquisition issues. It is focused on determining the method of measurements, such as strain, displacement, acceleration, temperature, wind speed, sensor placement and other related issues. It also deals with various possible excitation methods that can be deployed, such as ambient excitation, forced vibration or local excitation, and the type of data transmission, such as wired or wireless. Various parameters and methods are used in feature extraction and information condensation, including resonant frequencies, frequency-response function, mode shapes and mode-shape curvatures, modal strain energy, dynamic flexibility, damping, Ritz vectors, extracting nonlinear features, empirical mode composition, wave propagation, Hilbert transform, evaluation of auto-correlation function and other related features. Statistical model development involves two methods: supervised learning and unsupervised learning. Supervised learning includes response surface analysis, Fisher's discriminant, neural networks, genetic algorithms and support vector machines. Unsupervised learning includes control chart analysis, outlier detection and hypothesis testing.

In the case of health monitoring of a bridge, as shown in Figure 1.1, there will be varieties of sensors placed on the deck of the bridge. The sensors are the first-level components of the health monitoring system. In parallel, let us also look at the health monitoring of an offshore structure with multi-tier deck with drilling derrick, moon pool, living quarters, flare boom, helipad, etc. The offshore platform is supported on a template structure founded to the sea bed, as shown in Figure 1.1. There may be different varieties of sensors placed on deck and living quarters at various levels above

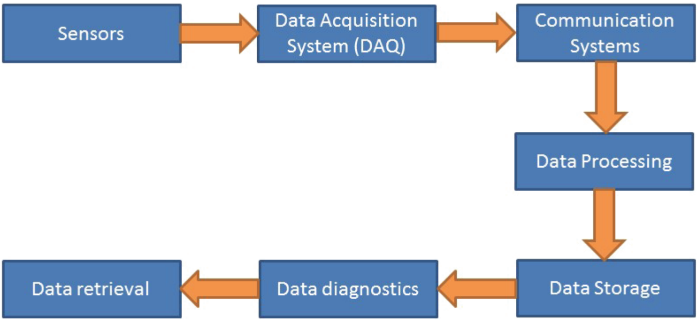

Figure 1.1. Components of SHM.

the water level. All these sensors need to be connected to a DAQ system, which is the second component in SHM. From DAQ using communication systems, they will be transferred for data processing. The communication system is the third component in SHM, which will collect the data for post-processing. The data processing is the fourth-level component in SHM. Once the data are post-processed, the data need to be stored; data storage is the fifth stage in SHM. It is also known as data repository. Stored data will be taken to data diagnosis and data retrieval. The layout in Figure 1.1 includes various components, which are involved in a complete health monitoring system used for infrastructure engineering starting from sensors to data retrieval. From the complete layout of SHM, one can divide them componentwise.

The vital components of SHM are as follows:

(1) **Sensors:** There are different types of sensors based on layout of topography, scalability, etc.
(2) **Data acquisition:** It depends upon the type of DAQ used, whether it is going to handle wireless or wired sensors, etc.
(3) **Communication system:** It can be done using either R/F frequency or Intranet.
(4) **Data processing:** It deals with the statistical analysis of the collected data.
(5) **Data storage:** It also requires data diagnosis and data retrieval.

Application complexities of various components with respect to different industries, such as aviation industry, civil infrastructure industry, mechanical industry, oil and gas petroleum industry, will be discussed later.

1.7. Sensors Used in Health Monitoring

(a) **Fibre Bragg diffraction grating sensors:** These are embedded in structures, which are laser marked with optical interference parameter. They measure the local strain caused by the deformation, which results in sensor measurement. These sensors will transmit a different wavelength, based on which the measured deformation can be detected.

(b) **Acoustic emission sensors:** These work on the basis of acoustic signals, which are generated by the presence of cracks or local faults. These sensors are useful to measure delamination of fibres or breakage.

(c) **Smart sensors or sensor coatings:** These are paints or coatings, which are applied on the surface. They remain integrated with the piezoelectric or ferroelectric elements to measure the strain variation. Sometimes, carbon nanotubes are also used to detect such variations. A detailed spectroscopic analysis is required to process the strain variation caused by the damages in the local scale.

(d) **Microwave sensors:** These are actually useful to indicate moisture ingression when embedded in structures. They are useful and efficient in composite structures.

(e) **Imaging ultrasonic sensors:** These contain an ultrasonic wave transducer, which generates a signal that passes through the material. Change in reflection indicates the flaws, presence of cracks or any other local damage.

1.8. General Challenges in SHM

Following are a few challenging scenarios that occur very often while implementing SHM:

- The foremost challenge in the SHM industry is the development and demonstration of the health monitoring technology, which can be useful to maintain the structural integrity with improved reliability and durability. There are many techniques by which health monitoring can be carried out and is being practiced all over the world. Undoubtedly, most of them are successful as well. However, at one point, it is agreed that developing a technology, which suits a specific application problem, is one of the most important and major challenges in the SHM scheme. Unlike conventional non-destructive techniques, a single technology of health monitoring cannot be suitable for all applications, which makes it more challenging. It depends on various factors such as material, component geometry and identifiable damage scenarios of a given structural system.
- Further more challenging is the fact that the outcome of monitoring scheme should be reliable because sometimes it may trigger an unwanted maintenance which is expensive. It may also sometimes create spurious warnings which should be avoided. Such situations generally degrade the confidence level on the strength of the existing structures.
- Next issue is the optimisation of structural design on the basis of data acquired or monitored through SHM. It is important that this data which is acquired through SHM should be fairly accurate and robust.
- The next challenge could be the major concern regarding the cost of the whole scheme.
- Furthermore, an important factor is related to the owners of the structural system. Even in the case of government undertaking schemes, the use of SHM needs to be scientifically established as it invokes public funding on a major investment. Therefore, it should produce a reasonably advantageous outcome from economic and public safety perspectives. It should be producing results that are debatable and comparable to the regular maintenance approaches.
- The next major challenge is actually the damage detection itself. This is related to the location of damage, origin, scalability, prospective growth and consequences.

- The other major challenge is reliability and robustness of the sensors, their lifespan, and adaptability to working environment and successful suitability to sensor network.

Some of the additional challenges in the SHM scheme include damage identification in civil and mechanical structures. For a given structural system, locating the damage itself requires a lot of experience and database comparison in order to identify the parameters causing such damage initiation.

1.8.1. *Comparison of structures with and without SHM in terms of reliability*

Figure 1.2 shows the comparison between two sets of operations, where one set of operation is with SHM deployment and other set without SHM. The quality of the structure in terms of its functional value is given by the reliability level and the maintenance cost. If there is a system which is without SHM, reliability of the system will be very high initially and then it decreases with the decrease

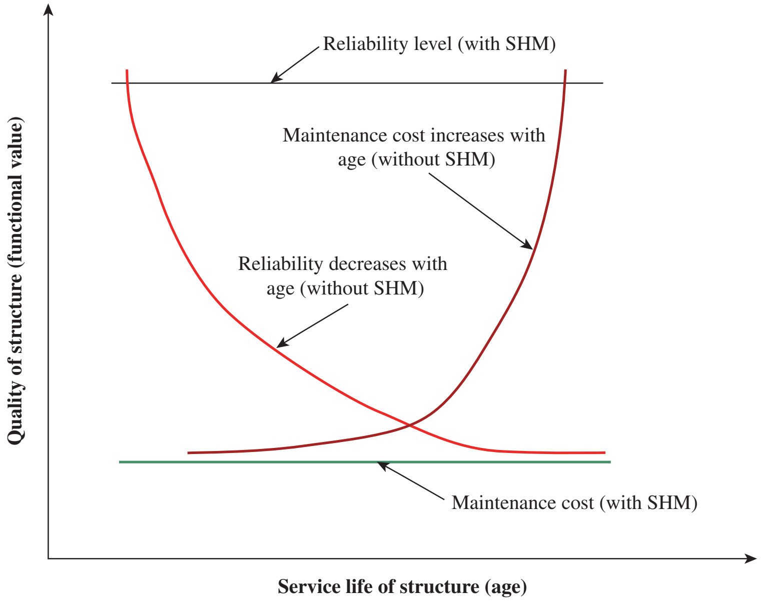

Figure 1.2. Comparison of structures with and without SHM.

in quality as the service life increases. This indicates that there is a reduction in reliability with age for structures without SHM. But the maintenance cost will also be increasing with age for structures without SHM. On the other hand, for the structural systems with SHM, reliability will keep on increasing with the age of the structure. Here, the system will have more or less constant maintenance cost and standard reliability level. So, deployment of SHM in terms of quality of the structural system and enhancement in service life can be achieved with more or less standard maintenance cost or lower maintenance cost, provided SHM is deployed using proper methods. Thus, structures with SHM deployment show more or less a constant maintenance cost, even with the increase in the service life of structure or ageing. It also shows a constant reliability level, indicating assurance of acceptable quality of the structure in terms of its functional value. Of course, without SHM, there is an increase in maintenance cost and decrease in reliability with ageing.

1.9. SHM Methods

Classification of SHM essentially depends upon the techniques used for damage detection. There are four levels of damage identification: (i) Level I, which is focused on the determination of damage in the structure; (ii) Level II, which highlights the determination of geometric location of the damage; (iii) Level III, which quantifies the severity of damage; and (iv) Level IV, which predicts the (remaining) service life of the structure after occurrence of damage. Based on the levels of damage, SHM can be executed in four stages: (i) operational evaluation; (ii) data acquisition; (iii) extraction of information and data processing; and (iv) development of appropriate statistical model for feature discrimination. We shall discuss these in detail in the following sections.

1.9.1. *Operational evaluation*

This stage consists of various factors, such as economic consideration, life-safety issues, definition of damage, details about environmental constraints, operational constraints, data collection and management.

1.9.2. *Data acquisition*

This stage depends upon the following aspects:

- **Excitation methods:** The choice of data acquisition system also depends on the type of excitation which includes forced excitation (number of channels, frequency and bandwidth depend on the type of excitation), ambient excitation (in this case, frequency can be low), and local excitation (forces will be of lower level) and global excitation (larger forces).
- **Data transmission:** Wired or wireless.
- **Sensing the structural responses:** This includes the types of responses measured from the structure, such as strain, displacement, acceleration, temperature variation, wind force and wave force.
- **MEMS technology for sensing**.
- **Fibre optic sensors**.
- **Sensor layout and location of sensors**, which includes scalability and power management.

1.9.3. *Feature extraction and condensation of information*

This is also referred to as data management and processing. There are various parameters and methods, which are used to extract the vital information which are required to assess the present health of the structure. A few of them are listed as follows:

- resonant frequency band;
- frequency response function;
- mode shape;
- mode shape curvature;
- modal strain energy;
- dynamic flexibility;
- damping introduced in the structure due to defect;
- anti-resonance characteristics;
- Ritz vector;
- canonical variant analysis;

- nonlinear features;
- time frequency analysis;
- empirical mode decomposition to know the higher order contributions;
- Hilbert transform;
- wave propagation;
- auto-correlation function.

1.9.4. *Development of statistical model*

This helps in identifying the vital parameters in assessing the structural health. This can be subdivided into two types:

- learning under supervision;
- unmonitored learning.

Learning under supervision deals with response surface analysis, fissures discriminate, neural networks and genetic algorithms, whereas learning under unmanned conditions deals with control chart analysis which is more or less automatic, outlier detection which will filter out the outlayered values in the recorded excitations, neural networks which also has the capability to train the system without supervision and hypothesis testing. Out of all the four components of the SHM process, the most difficult task is the choice of statistical model which helps us to extract the information related to assessment and monitoring.

1.10. SHM: State-Of-The-Art Application

Every system, whether it is mechanical, electrical or structural, has minor defects; this may be due to manufacturing constraints, poor quality control of material used for manufacturing or construction, improper design, effects caused by unforeseen environmental loads, etc. As long as these defects are minor and does not interfere with the functionality of the system, it may be acceptable; but they can continue to grow and result in a sudden failure, leading to catastrophic consequences. Such disasters can be predicted and avoided by deploying SHM; this essentially reduces to identifying defects (or damages) in the (new or old) system. While there are many methods available for damage detection, the SHM process depends largely on the technique used for damage detection. Therefore, identification and location of damage are very important, but no single method of SHM can address these problems, which can be commonly applied to all types of structures. This means that different techniques of SHM are practised and they all have damage-related dependencies.

One of the important factors in the SHM identification is sensitivity. Highly sensitive techniques may show false-positive positions of damage location; low sensitive techniques may show false-negative positions. Therefore, sensitivity of the sensors deployed is again problem-specific. Further, lifetime prediction of service life based on damage modelling is actually very difficult. Most of the techniques which use the service life prediction based on damage modelling are based on reduction and rigidity of the member, but reduction and rigidity must be related to strength. Otherwise, they are not useful for reliability estimates, which are an essential outcome of SHM evaluation.

1.11. Key Issues in Choosing SHM

There is a wide variety of non-destructive testing (NDT) methods and visual inspection techniques that are useful replacements of the SHM system. This is due to the main fact that sensors, which are permanently embedded in the SHM systems, make the process expensive. But, there exists a major advantage of using SHM in place of NDT methods. Measurements observed by the sensors in the SHM process are interpreted by software, which is responsible for processing and managing sensor information. One of the major differences between the traditional NDT and SHM systems is the integrated approach and autonomous inspection that are adopted in the SHM process, which makes the structures more intelligent. SHM is actually not a commodity to purchase but need to be designed and developed. SHM is problem-specific and it cannot be a generic system. High engineering cost and lack of resource availability leave no better choice for the designer, except to choose one of the existing health monitoring schemes or systems.

Unfortunately, most of the SHM systems rely on the point sensors. Point sensors obtain data at one point to monitor. They have a few limitations. Primarily, it is with respect to their insight and not with respect to their accuracy and reliability as these sensors are perfect, scientifically advanced and highly ultra-modern. When there is an event that occurs between the critical points where point sensors are installed, major information about the structural health will be lost. Secondly, it is with respect to the data normalisation. Data normalisation is the process of separating the data occurring from different changes in the behaviour of the structural system. This is essential as the sensor output contains combined information, which is complex to separate. They will include the damage caused by the environment, structures or material degradation, making it complex through combined representation. Therefore, non-continuous monitoring will not be helpful to normalise the data. The solution could be the usage of fibre optic sensors (FOS), whose application is well established by SENSURON in Europe. FOS can be fully automated to detect the local damage through continuous monitoring. Therefore, the system relies less on the interpolation of data. Since the data are continuous, it is also easy to attribute the changes that arise from various conditions, such as environmental factors, material degradation, etc. The use of FOS has long-term benefits and possesses a high degree of convenience to use.

As discussed in the International SHM workshop, SHM development can be divided into the following sequential steps: (i) detection; (ii) identification; (iii) quantification; and (iv) decision (Fu-Kuo Chang, Stanford University). While it is observed that detection is the lowest level of maturity that the SHM system should (at least) posses, a good quantification should lead to a correct decision and efficient solution. One of the most expected innovations in SHM could be bio-inspired sensor networks, which include a large number of small sensors, switches, processors with the accompanying software. If implemented in a massive scale, this will result in a higher reliability apart from being highly economical due to the large production volume and the capability of being installed in a large variety of structures; C-MOS and MEMS manufacturing techniques are lead-liners towards this modernisation.

1.12. Uncertainties in the SHM Process

Old existing structures do not show up any defect or deficiencies until they experience a disaster. However, it would be too late by then as the damage would have already occurred in terms of economic and human loss. Therefore, it is fundamentally important to design the SHM system, which is proactive in terms of private, public or national interest. In this context, continuous monitoring seems to be an effective solution. *In situ* monitoring, which is a continuous monitoring system, is capable of identifying major differences between vibration-based measurements and environment-based changes. This is one of the important sources of complexities, which actually confuse the data obtained from the sensors, to really work into the application of the measured data towards assessment or control design from the SHM scheme. But, continuous monitoring is expensive and it handles a big volume of data. So, the data communication, data analysis and retrieval can be a sort of challenge in terms of its volume. Certain researchers have also suggested the other alternative for this problem. One of the important alternatives for the above problem is numerical simulation. Numerical structural analysis is also used to predict the health of the structure. It can also avoid complexities that arise from continuous monitoring. For example, continuous monitoring of a bridge is considered. It may involve a lot of complexities including blocking of traffic, conducting expensive static and dynamic load tests, which are essentially cumbersome procedures. Alternatively, the damage status of the deck slab of the bridge can also be detected by analysing eigenfrequency or stiffness degradation. One of the important demerits of this alternate method is that the effects caused by local damage cannot be predicted or detected by this method. There are other specific issues with respect to capturing the time-dependent change in material properties. It is also difficult to capture the time-dependent change in the structural form and the loading pattern. Interestingly, these are the actual sources of uncertainties as well.

1.12.1. *Sources of uncertainties*

(a) ***General uncertainties*:**

(1) Exact modelling of external load events including its time dependency and space dependency is generally approximated by a set of independent events.
(2) Strength and stiffness degradation with space and time dependence are disregarded.
(3) Measurements of geometric data such as maximum deflection of the deck slab in the case of bridge displacement under dynamic load test are prone to a lot of human errors and inaccuracies.

(b) ***Modelling uncertainties*:** The structural modelling which indicates the modifications such as construction errors, changes in structural geometry (marine growth, crack propagation, etc.), change in material characteristics due to ageing, physical, chemical and mechanical degradations cannot be captured completely.
(c) ***Uncertainties from load variation*:** Load can vary with respect to time and space, and it cannot be captured completely.

1.12.2. *Solutions to uncertainties*

The above uncertainties can be handled in three ways:

(1) using random variables;
(2) using fuzziness;
(3) using fuzzy randomness.

1.12.2.1. *Randomness*

The data can be plotted as a typical power spectral density function by considering a probability distribution function and the randomness can be expressed as a PDF function as shown in Figure 1.3.

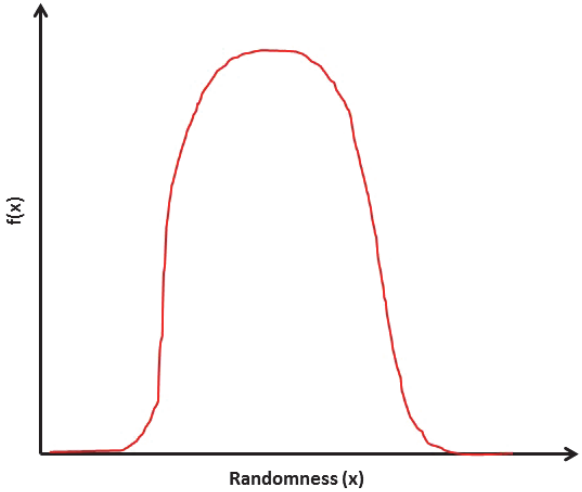

Figure 1.3. Randomness.

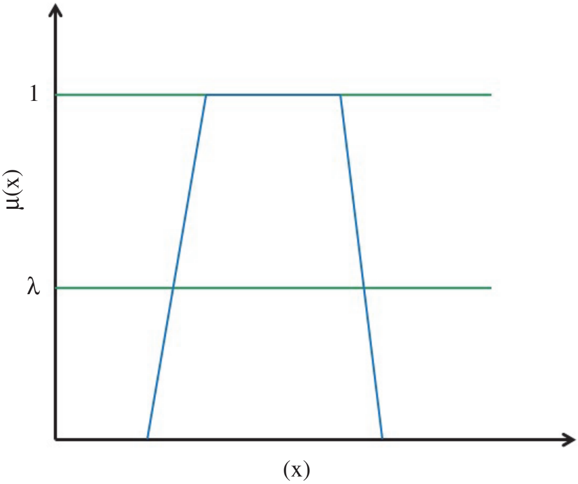

Figure 1.4. Fuzziness.

1.12.2.2. *Fuzziness*

This can be done by reporting data by using a fuzzy logic algorithm which can have a variation modelled typically, as shown in Figure 1.4.

1.12.2.3. *Fuzzy randomness*

This is a combination of fuzziness and random variables which can handle fuzzy randomness, as shown in Figure 1.5, where fuzziness is operated for a particular band and randomness is chosen within the band.

The selection of the model among the above three depends on the availability of the data as these three models are very strongly data-dependent. The quantum of data and quality of data available to represent uncertainty will decide the type of model. For example, if the data are statistically sound, then the parameter can be described once stochastically. But even in this case, appropriate choice of probability distribution will actually affect the results of simulation significantly. On the other hand, if the data of parameters are frequently fragmented and they are not continuously distributed without precision, then fuzzy randomness model is more effective to model this uncertainty.

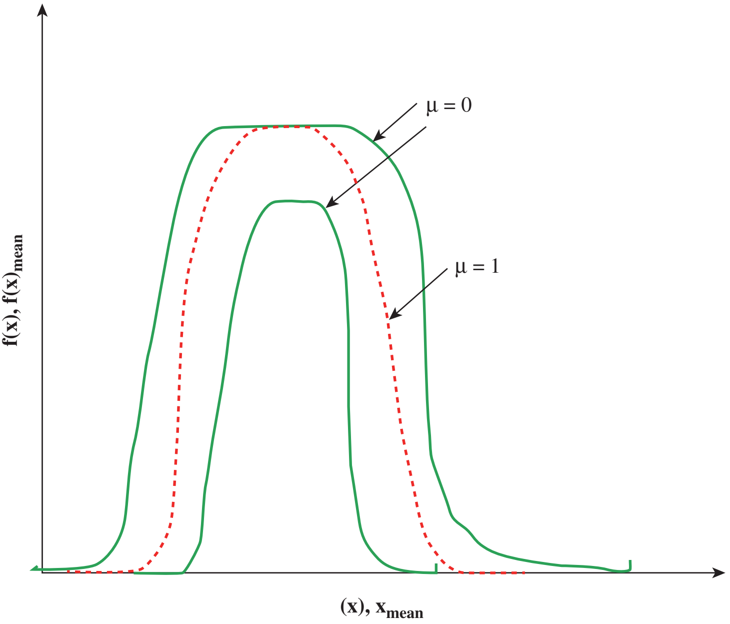

Figure 1.5. Fuzzy randomness.

1.12.3. *Other classes of uncertainties*

(1) Uncertainties present in the observational data may arise from experimental or numerical analysis. This can be handled by statistical sampling, hypothesis testing and input−output effect analysis methods. These will be useful to characterise the effects caused by the uncertainties on the output of analysis.

(2) There are a few issues related to the advancements in SHM, which can also cause uncertainties. The SHM process, in the present context, is highly advanced. It has got wireless decentralised sensors, which are recent advancements in semiconductor devices and MEMS technology. While they are useful to collect *in situ* data efficiently, they are also capable of establishing communication requirements between the sensors; this makes the decision-making process much faster. However, investigation of the collected data is a critical issue as this needs a faster investigation process. Even though the data are huge in the case of continuous monitoring, modern statistical tools are capable of handling this volume without leaving any residual error. For example, statistical pattern recognition (SPR) can be one of the effective tools. While doing statistical analysis for a set of observations, it is interesting to note that they follow a pattern. Instead of analysing the new set of data every time, this statistical pattern is identified, which makes the process easier. Further, it also simplifies data condensation and feature extraction from the data. SPR plays an important role by offering a major solution to address the uncertainties related to volume of data; this problem is precarious in the case of continuous monitoring of structures.

(3) The most critical issue is data normalisation, which is a process of qualitative separation of data of vibration-based results from that of the data based on environmental conditions; this is done through a statistical prognosis. Even in the stage of statistical prognosis, uncertainty influences service life prediction; time and space dependency characteristics of material resulting from this is very complex. Further, load variations which are also time- and space-dependent add to the complexity.

1.13. Health Monitoring of Ocean Structures

Offshore structures are huge and massive structures, which runs over a large span with heavy mass concentration spread over the entire area. In addition, deep-water platforms need a huge capital investment for their installation itself before it starts its operation to earn revenue. They have many people working onboard during their operation time. Therefore, offshore platforms are too expensive as their downtime could cause a huge financial loss. Most of the offshore platforms in the recent past are planned to operate under unmanned conditions; they are designed to be self-operating and self-producing. In such cases, continuous monitoring is very vital to ensure proper functioning of the platforms. Marine structures like coastal jetties should not be frequently intervened for repair because this could affect the functional value of the system. These structures demand preventive maintenance while the system remains functional. So, structural repairs should be carried out without the shutdown of the system. Most importantly, these structures need to be repaired when they are loaded. In order to understand the response behaviour under such loading conditions, it is important to have a continuous monitoring.

Ocean structures are assigned with special operations like coastal protection, dry-docking, berthing of vessels, coastal defence systems and marine police stations, etc. Safe upkeep of these structures ensures serviceability throughout their life. Four activities that are vital for their upkeep are as follows: (i) condition assessment; (ii) periodic maintenance; (iii) controlled inspection; and (iv) safe operations. Critical factors that influence repair of such structures include the following:

- The structure shall remain in service during repair as a total shutdown is not permitted due to emergency demands that may arise any time.
- The repair methods proposed should be cost-effective and impart long-term solutions as frequent interventions into such structures for repair is not permitted.

- The repair procedures are invoked only under emergency situations and hence continuous monitoring is required to assess the current state of health of the structure to recommend appropriate repair solution.

Having known the fact that visual inspections that are used for routine condition assessment of ocean structures pose serious limitations, recent studies showed their slackness in the desired levels of reliability. It is a common practice to carry out repair of cosmetic type whenever visible damages like cracks, spalling of cover of concrete, chemical deterioration and corrosion are noticed. Inspection helps to identify signs of damage, but correlating them to condition assessment is highly problem-specific and is quite tedious. Unless continuous monitoring is carried out, one will not be able to justify the necessity for any kind of repair in ocean structures. This is due to the fact that these structures cannot be intervened for repair procedures until a thorough reasoning is established.

Some of the major factors influencing accidents in offshore structures are due to poor maintenance, lack of communication between maintenance and operation staff, delay in scheduled maintenance, inadequate maintenance and safety procedures (Chandrasekaran, 2016a,b; Okoh and Haugen, 2013). Damage scenarios are due to various reasons, which include ship impact on the structure, fatigue and damage due to corrosion. Researchers have simulated the damage either by inducing a crack or by removing the member. Experiments are performed on the scaled platform tested in lab to detect the self-induced damages (Begg *et al.*, 1976). In real-time implementation of health monitoring, an attempt to carry out measurements below water line will be expensive and could be highly rational as divers are employed for measurements. Alternatively, measurements below water line can be carried out using underwater sensors with wiring, for which the wiring has to be done at the time of construction of the platform. In such cases, corrosive saltwater environment is an important factor to be considered for the long-term monitoring.

Offshore structures operate under high-risk factor due to the kind of process involved in exploration and production. Apart from being novel and expensive of its kind, their failure may lead to serious environmental pollution and economic loss as well. To avoid such serious consequences, it is better to follow the preventive maintenance approach, which shall depend on continuous monitoring of the structure under time-varying loads. In the case of offshore structures, it is difficult to carry out traditional inspection through NDT or visual inspection as the structure is huge and partially submerged in the water while manual inspection is not possible in all locations. An automated monitoring like SHM using sensors will be an effective tool to assess the status of the platform based on the damage analysis to ensure safe operability.

In the case of offshore structure, as most of the areas are not accessible for measurement, damage assessment scenarios are generally examined through simulated numerical models while a few on the scaled models are analysed through experimental investigations. It is seen as a good practice to analyse changes in response of scaled platforms under different loads during experimental investigations and extrapolate the data for failure analyses or correlate these data with those measured on the real platform. While deploying SHM in offshore structures, certain assumptions and approximations are important for a convenient procedure. They are as follows: (i) varying mass is not linked with the marine growth, equipment and fluid storage; and (ii) variable submergence, leading to change in buoyancy and mass of structural members, is not included and it will alter energy dissipation of the system (Brincker *et al.*, 1995). Based on the studies reported in the recent past, factors that govern the design of monitoring system for offshore platforms are as follows (Loland and Dodds, 1976):

- Sensors should withstand environmental uncertainties.
- Proposed SHM scheme should have financial advantages over the traditional (manual) inspection method.
- Vibration spectrum should remain stable over a period of time.
- Normal sea state and wind excitation shall be used to extract the resonance frequency.
- Above water measurements should be used to identify mode shapes.

1.13.1. *Damages*

Damage is defined as the change in material properties, or the change in geometric characteristics of the system, which adversely affects its current or future performance. This also includes change in boundary conditions and system connections, which can lead to adverse effects due to their degradation. Damage is not meaningful without comparison between two system states: initial and damaged ones. Damage assessment can be simplified by answering the following questions: (i) Is there a damage in the system? (i.e., identification of its existence); (ii) Where is the damage in the system? (i.e., identification of its location); (iii) What kind of damage is present? (i.e., identification of the type of damage); (iv) How severe is the damage? (i.e., evaluation of the extent of damage); and (v) How much of useful life remains? (i.e., prognosis). Answers to the above questions can be readily obtained by using non-destructive tools and by employing non-destructive evaluation methods (NDT/NDE). These tools are very helpful in identifying the damages at the global level. For example, damages on the structure as a whole can be identified but cannot be precisely located at the local level on each member. In the case of reinforced concrete structures (RCC), this problem is more serious due to increased complexities arising from embedment of reinforcement.

While SHM is the process of implementing damage detection strategy for engineering infrastructure, usage monitoring measures input to the structure and its response to these inputs before damage, which can assist in identifying the onset of damage and deterioration. Prognosis is the coupling of the above information of SHM and usage monitoring under given environmental and operation conditions, component- and system-level testing and modelling to estimate the remaining condition and useful service life. One of the recent approaches, which can handle this problem is statistical pattern recognition (SPR). Damages generally initiate at the material level. They are called either defects or flaw. Under certain loading conditions, these damages tend to propagate and they can result in system-level damage. The main concern is not the system-level damage; it is the component-level damage. It is very important to note that the damages do not refer to loss of system functionality. If the system functionality is lost, it is called as failure. Damages prevent the system from performing in its optimal manner. Damage degrades the performance of the system. It does not affect system functionality completely whereas is a total loss of functionality. Damages can be corrected whereas failure needs to be mitigated, where the system has to be reconstructed. So, the purpose of SHM is to avoid failure. Damage cannot be avoided because it is an inherent property of the system which leads to loss of functionality owing to material degradation, excessive loading, excessive deformation, etc. Damage cannot be prevented, but failure can be avoided. Thus, health monitoring will address the failure of the system, which is a total loss in functionality.

Damage to a civil and structural system can occur in two timescales: long-term timescale and short-term timescale. Damages in the long-term timescale can be caused by corrosion and fatigue, while those in the short-term timescale can be caused by impact loads, shock loads and aircraft landing in aviation industries. SHM can be redefined as a process of implementing damage identification strategy. This process involves the following:

- Observation or monitoring on a continuous scale;
- *Assessment based on the extracted data of damage scenarios*: It depends upon the sensitive features identified to quantify damage and the statistical analysis tools which are used to quantify damage. This will help in determining the current state of the structural system. In this process, non-destructive evaluation plays a very important role. It is primarily used to characterise the damage and check for severity when there is prior knowledge of the damage.

1.14. SHM Challenges

Vibration-based damage detection is a very useful and successful tool which is used in civil structures, especially bridges. The outcome of the study is generally modal parameters which are useful as primary features to identify the local damages caused on the deck slab of bridges. They are capable of locating the damage to a larger extent. One of the major concerns in applying SHM to civil infrastructure is the physical size of the structures. In the case of bridges with very long-span deck slabs spread for kilometres, it is very difficult to have sensor network in terms of its reliability, data transmission and its functional robustness. It can be one of the difficult areas to diagnose in terms of the application of SHM on civil infrastructures.

Under the cloud of vibration-based monitoring techniques, one of the basic challenges of SHM is feature selection as this significantly affects stiffness, mass and energy dissipation properties of a system being monitored. Structural damage is a local phenomenon, which may not influence the global response of the structure in lower frequencies, when measured under normal operating conditions; but to ascertain the extent of damage, responses in lower frequencies are equally important. Another important challenge is the training of the SHM system for feature selection and damage identification under unsupervised learning mode. Actually, as data from damaged systems are not available instantaneously, accumulation of damage over wide-varying timescales pose significant challenges. A more intrinsic challenge is the choice of the appropriate sensor system and an accommodative network, which can remain functional even when the structure is expected to get damaged. To be very precise, even upon failure of a sensor, the damage identification algorithms should be capable of adapting to a new (available) alternate network. Researchers recommend the use of self-validating sensors or the use of sensors that report on each other's working conditions. The most important non-technical challenge is to convince the structural system owner that the SHM technology will provide an economic benefit over their current maintenance approaches; convincing regulatory agencies that SHM will provide life-safety benefits is an add-on to this challenge.

1.14.1. *Challenges in the oil and gas industry*

Oil platforms are generally inaccessible for damage inspection. So, vibration-based techniques have been tried for damage identification in the early 1980s in oil industry. There are some specific issues which make this application a highly challenging technique. The major challenge is that the damage location is not known because majority of the area of the platform is inaccessible for measurement. The most common solution is to simulate the damage scenario using numerical model in a software and examine the severity to interpret the damage. There are major concerns in using vibration-based damage detection in oil platforms. They are as follows:

(1) The machine noise created by the platform interferes with the measured vibration.
(2) Instrument deployment in hostile environment is also a challenge.
(3) A faulty mass representation arises due to marine growth. In vibration-based damage detection, natural frequency of the system is the major parameter, based on which damage is characterised. Natural frequency is a function of stiffness and mass of the system. When there is a faulty mass which arises on the platform due to marine growth, it does not give the damage characterisation exactly as simple as it is applied to other structures.
(4) The varying hydrodynamic mass arises from the fluid storage variation.
(5) Variation arises in the foundation condition in due course of time.
(6) Absence of wave force as exciting force in higher modes also poses challenges.

The above factors or concerns have limited or restrained the use of SHM in the oil industry, especially on oil production platforms. But they are very well and continuously used in ships.

1.14.2. *Challenges in the aviation industry*

In the aviation industry, the vital component for measuring the responses will be on the aircraft. Aircraft are essentially metallic structures, which are designed for specific flight hours. Generally, aircraft are retired from flying once they reach predecided flight hours. Alternatively, if they complete predecided landing cycles, then too, they can be retired. However, if you really do some real-time fatigue analysis and damage assessment of aircraft, especially during landing cycles, then it is possible to extend the flight hours or to preretire them, which improves public safety. One of the methods by which this can be achieved is the use of strain gauges and mechanical strain recorders to measure the stress deviations, particularly during the landing cycles. The second application could be the use of flight data recorder (FDL) using electromechanical mission computer (EMMC). Both methods are very useful in estimating the life of an aircraft and its fitness for 'n' number of flight hours in the future. In both cases, the use of SHM is clearly seen as a major advantage. This can be helpful to decide the suitability or fitness of the aircraft. It is also helpful to modify the design philosophies which are essentially arrived at based on continuous monitoring. There are some anomalies which can be very well explained through the SHM applications if they are in practice. They are as follows:

- The first anomaly is with respect to the statement in aircraft design: "Aircraft geometric configuration is not related to the structural load disbursement." By continuously monitoring the stress values, this assumption can be proved wrong. It is found that the aircraft geometry or configuration makes a significant difference on structural loads.
- The second anomaly states that the "usage of all aircraft in a large fleet averages out with time". This can also be proved to be wrong through continuous monitoring because this is not true based on fatigue assessment. The fatigue damage depends on the actual usage and hence cannot be averaged for a large fleet.
- The third anomaly is based on the maintenance management, which can be planned on the basis of design load spectrum. SHM will definitely help in following the actual measurements of the stress variations. Based on this fact, it was found that average user spectrum is more severe than that of the design spectrum.

Thus, the major anomalies in the case of geometric configuration, average fleet time and in the usage of design load spectrum can be easily understood in a better format when the aircraft is continuously monitored for its performance during landing and take-off processes (Khan *et al.*, 2014).

1.14.3. *Tools of SHM in the aviation industry*

The common tools used for removing the anomalies in the aircraft or aviation industry based upon health monitoring are as follows:

(1) fuzzy pattern recognition;
(2) neural networks;
(3) diffused ultrasonic-waves technique to detect the structural damage present in the unmeasured temporary members;
(4) vibration-based technique;
(5) intelligent parameter varying technique for the location of damage;
(6) novel sensor layout in SHM.

If you look at the maintenance of aircraft structures, one can see the use of health monitoring playing a major role in their successful maintenance. Figure 1.6 shows the parameter contributing to the maintenance of aircraft, where a severe usage pattern is compared with design usage pattern and mild usage pattern. The hatched portion above design usage line clearly shows the safety risk region. The shaded portion below design usage line shows the potential life enhancement region. This figure shows that the severe usage represents the loss of life due to non-SHM. The safety risk region clearly shows the advantage of enhancement of life due to the usage of SHM. Thus, the application of SHM can help in checking the underuse of service life of an aircraft and it can enhance the service life or usage value of aircraft by continuously monitoring its stress distribution levels.

In this context, researchers also recommend passive SHM and active SHM. Passive SHM deals with the observation of a structure as it evolves. Basically, a physical parameter and its state of evolving as a result of interacting with the environment is examined; tools used could include, e.g., acoustic emission. Active SHM deals with a system where a structure is equipped with both sensors and actuators. This is highly suitable for structures which are unmanned.

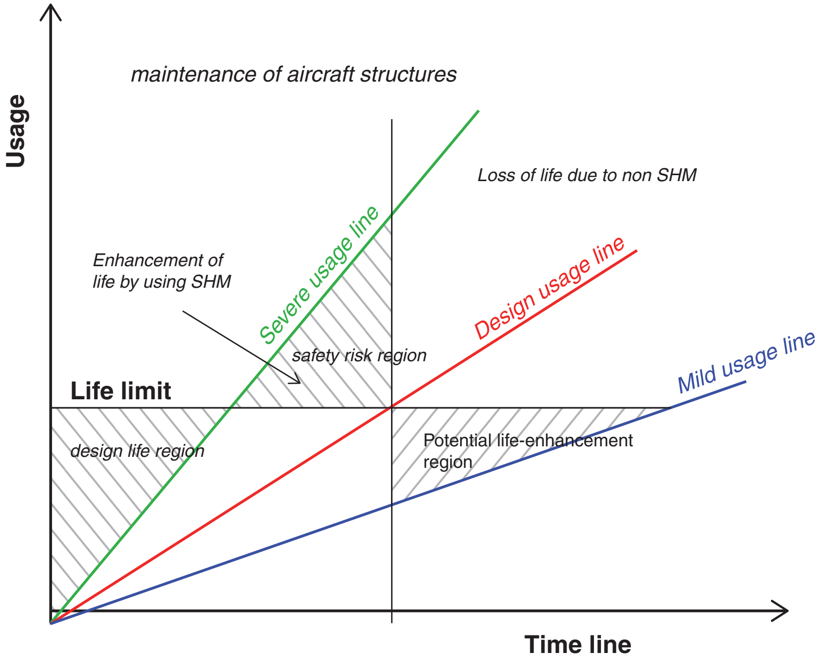

Figure 1.6. Components in the maintenance of aircraft structures.

In such cases, the actuators prompt forces opposite to the structural motion and intuit a recentering capability of the platform or the system under environmental loads. There are many aircraft, which are embedded with the SHM systems. One example is Boeing 787 Dreamliner, which is equipped with embedded sensors for continuous health monitoring. The location of these sensors is very important; generally, they are located in shell fuse legs, lower wing skin and door shutters. These are the places where the probability of damage is relatively high during loading.

1.15. Successful Deployment of SHM

The basic components of SHM are sensors, actuators, smart structures, smart materials, computational systems, signal processing and statistical models, as shown in Figure 1.7. There is a small overlay of

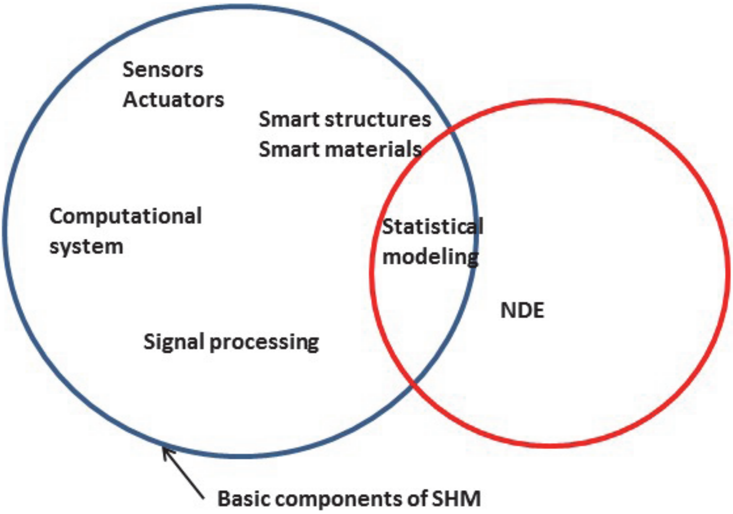

Figure 1.7. Basic components of SHM.

NDE with basic components of the system. NDE is a vital component integrally connected to SHM.

1.15.1. *Recently deployed NDE techniques*

(i) **HELP:** This refers to hybrid electromagnetic performing layer. This method is an alternative to a fully integrated electromagnetic technique which is quite expensive. In this method, by embedding the network of conductors in the material or by bonding the network of conductors on the internal surface of the structure, health monitoring is carried out. In this process, a grid which is a sensitive magnetic field is created. This field is created by an external electromagnetic antenna which crosses the structures. This is made of conductive composites, e.g., epoxy composites, carbon composites, etc.

(ii) **Ultrasonic vibrothermography:** In this case, lamb waves are used to generate ultrasound. The embedded piezoelectric patch monitors the surface thermal field with the help of camera. This field is produced by the interaction of lamb waves with the structure having defects (crack, fissure and delamination). This technique is very helpful to study delamination in composites.

(iii) **Lock-in shearographic imaging of ultrasound:** Shearographic imaging is created or generated by piezoelectric patch, which is generally embedded on the surface of the structure.

The above methods are very advanced and helpful in assessing the actual control and health of the structural system to a larger extent.

1.16. Axioms Used in the SHM Process

There are some common axioms used in the SHM process which are very useful and interesting.

Axiom I: All materials have a few inherent flaws or defects.

Axiom II: The assessment of damage requires comparison of the two systems. Damage assessment is always relative (with respect to another system). It is always on the comparison mode.

Axiom III: Unsupervised learning mode can be helpful in the identification and location of damage.

Axiom IV: Sensors cannot measure damage. The data collected or acquired are to be processed to extract featured values which can then be used to detect or quantify damage. Thus, the vital part is the signal processing of collected data and the statistical classification of the data to convert the sensor data into damage information.

Axiom V: The more sensitive a measurement is to damage, the more sensitive it is to change in environment and operational conditions. It means that there is a very high possibility of noise mixture with the damage data. Hence, it is important that one should intelligently extract the featured information from the recorded or acquired data.

Axiom VI: It is related to the sensing system. The SHM sensing system strongly depends on length (period) and timescale associated with the damage initiation and evaluation. For example, if a damage is a long-term phenomenon, then the damage propagation in terms of its timescale can be lost if not handled with appropriate sensing system.

Axiom VII: There is a strong correlation between sensitivity and damage. Therefore, the algorithm used to extract featured information based on which damage will be quantified should be carefully chosen and it should be free from noise reflection capability.

Axiom VIII: The size of the damage that can be detected from an SHM system changes with the dynamics of the structural system. It is inversely proportional to the frequency range of the exciting force.

1.17. Real-Time Monitoring of Buildings Under Seismic Excitation

This is a case study which is applied to a set of buildings post earthquake at San Francisco (Çelebi *et al.*, 2004). It is studied after the 6.0-magnitude earthquake at San Andreas, the peak ground acceleration of this earthquake exceeded 0.25 g, which is expected to cause considerable damage to different types of buildings. The objective of this study is that the owner of the buildings wanted to assess the safety of occupancy after the earthquake. A real-time monitoring was deployed to carry out this assessment. The requirements of this scheme are as follows:

(1) The systems must facilitate a rapid assessment of building integrity based on which the occupant safety can be declared following the earthquake.
(2) The SHM system must provide data like drift ratio, which is related to the earthquake damage. They can be used as indices to quantify the occupancy level of the system post earthquake.
(3) SHM should also have the capability to deliver data within few minutes after the occurrence of earthquake.

The SHM system recorded the following:

- The SHM system waits for an event.
- Once the event occurs, it produces a low-amplitude data in real-time analysis and starts making assessment of the data.

- Data provided by the system is very useful for post-seismic assessment.
- Based on the structural type and the damage assessment made, condition of occupancy post earthquake was to be declared based on different guidelines (e.g., FEMA).

1.18. SHM Issues in Concrete Structures

Concrete is one of the favourable construction materials for offshore structures and civil engineering structures. Nevertheless, concrete has shown greater advantages of structural use because of its strength, availability, application criteria and different structural forms which can be amendable using concrete as a construction material. However, there are some specific issues in health monitoring of concrete structures, which require a fundamental understanding. There are specific kinds of NDE methods which are very useful and particularly powerful when applied to concrete structures. In general, issues arise due to the special kind of problems in concrete structures. They are affected by a variety of issues. Fundamentally being heterogeneous material, issues are further complicated. When we talk about strength degradation, concrete has several ways by which strength is degraded. They are chemical degradation, physical degradation and mechanical degradation.

Examples of problems in concrete are related to the following: (i) chloride penetration; (ii) sulphate attack; (iii) carbonation; (iv) freeze–thaw cycles; (v) shrinkage of concrete; and (vi) issues related to mechanical loading on concrete structures. Chemical degradation includes corrosion of reinforcement, chloride penetration, carbonation, leaching of concrete, concrete under acid attack, sulphate attack and alkali aggregate attack. Physical degradation includes temperature variation and associated thermal expansion or contraction. There can be issues causing physical degradation also arising from the variation of relative humidity which is very important in coastal structures and issues associated with drying shrinkage and wetting expansion. Frost attack, wear and tear and abrasion can also cause physical degradation. Mechanical degradation arises essentially from externally applied load which can sometimes cause overload or impact load. There can be issues due to fatigue loads, differential settlement of foundation of concrete structures and seismic activity.

1.18.1. *Influence of degradation on concrete*

Concrete degradation can alter the properties significantly as follows:

- These degradations can alter porosity and permeability of concrete.
- It can further initiate or aggravate different material flaws, such as scaling, spalling, swelling, debonding, cracking, disintegration of concrete, etc.
- The degradations can also cause impairment in water tightness of concrete members. Especially reservoir structures, dams, overhead water tanks can also be affected very severely by this condition.
- It can ultimately reduce the load-carrying capacity of the member.

1.18.2. *Major challenges and solutions*

A major challenge in monitoring the health of concrete structures is that the damage under different deterioration processes accumulates at different rates. The timescale variation of these degradations is different. They get integrated and mixed to alter the behaviour of concrete. Therefore, there will be a multi-physics degradation process which needs a special type of analysis that can account for different timescales in different processes of degradation. If a numerical analysis is required to be carried out, then the governing differential equation (time-variant and space-variant) should account for the coupled physical and chemical process dependency. It should characterise the following:

(1) mass energy balance;
(2) thermodynamic and chemical equilibrium of the coupled heat conduction, ionic diffusion, moisture transport phenomenon and the corresponding chemical reaction.

Therefore, it is very complex to analyse this numerically. The major factor that contributes to the degradation of concrete should be identified. Interestingly, ordinary concrete possesses a high porosity and low permeability. Now, the interconnected pores or micropores and microcracks in concrete contribute to the permeability. Therefore, this makes concrete more vulnerable for deterioration. It is actually the rheology and crack structure of concrete which makes it complex. So, health monitoring of concrete is not a physical process. It is also not an electronic process where one can simply measure the strain values, displacements and deformations. It is also not purely a chemical process because it also contributes from other sources which are physical and mechanical. So, health monitoring of concrete essentially becomes multi-physics-dimensional problem.

1.19. Non-destructive Evaluation

There are many non-destructive evaluation (NDE) methods which are exclusively available for concrete structures and they can reasonably give good health condition for concrete structures. Some of the NDE methods suggested by Clayton (2014) are as follows:

(1) shear wave ultrasound;
(2) ground penetration radar;
(3) impact echo analysis;
(4) ultrasonic surface wave analysis;
(5) ultrasonic tomography.

In addition, for large volume structures, one can also use full-field imaging techniques, e.g., gravity-based platforms, nuclear reactors, etc.

1.19.1. *Full-field imaging techniques*

These techniques are useful for concrete structures, which essentially can be applicable to large volume structures.

(1) **Infrared imaging:** It tracks the thermal load path in a material, travelled longitudinally over a period of time. The onset changes in the load path changes the composition of the material which is an indication of the mechanical damage caused to the material. This method can also be combined with acoustic source or stand-off acoustic sound pressure technique to quantify the extension of damage. In this case, material is insonified with acoustic source and the full-field vibrothermograph measurements are recorded to characterise the material.
(2) **Measurement of the thermal response under an applied uniform heat flux:** Thermal gradient in the material is measured and analysed to identify the non-uniform material composition which essentially arises from the material defect that can then be characterised. There is another method which can be useful in large volume concrete structures.
(3) **Digital image correlation (DIC) technique:** This is useful to detect microcracking in the chopped fibre glass compressive moulded parts. DIC image shows principal strains in the damaged regions where cracks are formed. This method is useful to detect localised residual stresses, which are caused in the material upon removal of load. This can also be used to track the strain variations that occur under temperature variations.
(4) **Velocimetry:** This method is useful to detect the sub-surface nonlinearity caused due to material damage. For example, when a composite structure is subjected to ambient vibration, changes in strain variation can be analysed to detect the damage. In such cases, the damage indices quantify the degree of nonlinear stiffness and nonlinear damping, which are generally observed locally at each measured point on a grid of the member.

1.20. Sensor Performance and DAQ

Quality of data in health monitoring system depends on the performance of the sensors. Some common factors that govern are data format, precision and accuracy, linearity of data, dynamic range, cross-talk, durability, maintainability, redundancy, calibration and its cost. Structural health monitoring involves detection and tracking. While the first step is to make the sensor reading correlated with the sensitivity of damage, tracking involves establishing the relationship between the damage features and the damage levels. In general, there are two approaches in which the SHM system is developed. The most common strategy for developing the sensor network for SHM is to deploy an array of sensor network with the commercially available components. The excitation of the structure is limited to the range of frequency of this array of sensors. Physical quantities are measured without any definition of the damage that has to be detected, with an assumption that these measured data will be sensitive to the damage (Farrar *et al.*, 1994). This is based on the assumption that damaged and undamaged structures are subjected to a similar kind of excitation. Such strategy is deployed in real time, which will measure the data and analyze the data for damage-sensitive features. The alternate strategy is to quantify the damage through some process before developing the sensing system. Based on the available numerical simulation results, damage location and type of sensors are chosen. The extraction of damage features and statistical pattern recognition will be a part of the data analysis, which will be vital in the development of the data acquisition system (Flynn, 2010). Additional requirements are updated based on the changing environmental and operational conditions. The latter ones with the initial prediction about the damage by numerical simulations improve the probability of damage detection.

Types of data that need to be acquired should be defined to design the sensor network system. Two major types of data are as follows: (i) kinematic quantities and (ii) environmental quantities. Kinematic quantities include displacement, velocity, acceleration and strain. Traditional types of sensors are used to measure these dynamic responses. Accelerometers, displacement transducers and force transducers like load cells are some of the sensors used in SHM. Environmental quantities include temperature, pressure and moisture content. These parameters not only affect the damage level of the system but also have an impact on the operation of the sensors.

1.21. Need for Wireless Sensor Networking

SHM is a typical field in which the application of wireless sensor network (WSN) is useful both to measure damages and for online monitoring. Due to the reducing price and advancements in recent technologies of sensor networking, it is now easy, simple and affordable to have WSNs in lieu of the traditional wired SHM. Wireless SHM reduces the system cost and the installation time. In addition, it eradicates the installation of lengthy cables and thereby reduced complexities are involved in their laying and in-service maintenance. While the wired system depends on the centralised server, wireless nodes do not rely upon a central server. They convert the measured data into a digitised form and transmit them directly. Wireless SHM makes online monitoring more simple with low-cost computing processor. Recent innovations in the wireless SHM leads to the migration of computational power from the centralised data acquisition system to the sensor nodes.

1.22. Critical Issues in SHM

Though SHM has a wide variety of applications in various fields, there a few critical issues as follows:

- Uncertainties can arise from parametric data owing to the physical experiment and numerical simulation output.
- The imperfect knowledge of the control parameters of the physical experiment and numerical simulation also adds to the imperfect knowledge on the input to numerical model.
- Uncertainties can also arise from stochastic equations of motion, environmental variations, measurement errors which are human-based, discretisation and numerical errors.
- Uncertainties can also arise from the probability density functions of specific probability distributions. Probability density functions can handle problems related to uncertainties using random theory. So, one can choose a specific type of distribution to include all possible values of the variable. Other methods of handling this uncertainty are as follows:

(1) Dempster–Shafer theory of possibility and belief;
(2) theory of fuzzy set;
(3) information gap theory;
(4) convex model of uncertainty.

- The simpler way to address this uncertainty is the Monte Carlo technique. It is an idea towards randomly picking values of a parameter such that the histogram of the chosen values approximates the probability density function. Subsequently, the computational mode is analysed or evaluated at each point sampled in the input parameter space.
- Although many methods exist for the identification and location of damage, no single method solves all problems in all structures.
- The SHM techniques and process have damage-related sensitivities. While a sensitive technique produces false-positive results, less sensitive technique shall produce false-negative results.
- More nonlinear parameters are used in the SHM process, making the process more complex.
- While most of the traditional detection methods are based on appreciable reduction in the rigidity of structural element, quantification of damage and life prediction is more complex. This is due to the fact that correlating reduction in rigidity to decrease in strength is a difficult task.
- Although the SHM process has shown a lot of errors that may arise from experimental investigations, incompleteness and environment-related problems, statistical methods are very effective in handling them.
- Statistical pattern recognition (SPR) enables reduction in the number of sensors to be deployed for SHM but still requires advanced research to ensure correlated results that are authentic and safe.