1 Introduction

1.1 BASICS OF HEALTH MONITORING

Health monitoring is the scientific process of nondestructively identifying four characteristics related to the fitness of an engineered component (or system) as it operates:

(a) the operational and environmental loads that act on the component (or system),
(b) the mechanical damage that is caused by that loading,
(c) the growth of damage as the component (or system) operates, and
(d) the future performance of the component (or system) as damage accumulates.

Knowledge of characteristics (a)–(c) is combined with component design criteria and system operational specifications to identify characteristic (d), which determines whether or not a component will perform satisfactorily in the future. Health monitoring technologies must be nondestructive (e.g. should not involve cutting a part open to inspect it) and are ideally implemented online with embedded hardware/software in an automated manner as a system operates. Humans constantly apply health monitoring methods in their everyday lives. For example, a 'purr' or 'humm' is a sign that an automobile engine is working properly; on the contrary, a 'clank' or a 'clunk' is a sign that the engine should be fixed. This type of comparison between healthy and unhealthy signatures is the foundation of many health monitoring techniques. Figure 1.1 illustrates the basic aspects of health monitoring applied to an unmanned aerial vehicle (UAV).

Loads due to landing, aerodynamic forces, engine thrust and foreign object impact are shown acting on the aircraft. These loads cause the aircraft to respond by deforming and vibrating during operation. For example, compressive loads in the landing gear during touch down transmit through the aircraft to the stabilizer struts. Sensors inside the aircraft measure signals, which could indicate the vibration amplitude and frequency content along with the strain and so on. There are also environmental factors including corrosive and temperature effects, for instance, in the propeller bearings. These environmental factors can accelerate how quickly damage such as spalling (flaking of material) in the bearings initiates and grows. Measurements of environmental variables such as temperature might be made in the engine housing, whereas measurements of ultraviolet radiation or humidity might be made on the wing spar because composites can degrade when these levels are high. When a crack forms in the metal stabilizer strut as shown, changes in the vibration response indicate the presence of a crack. Damage in components such as the wing spar can consist, for example, of

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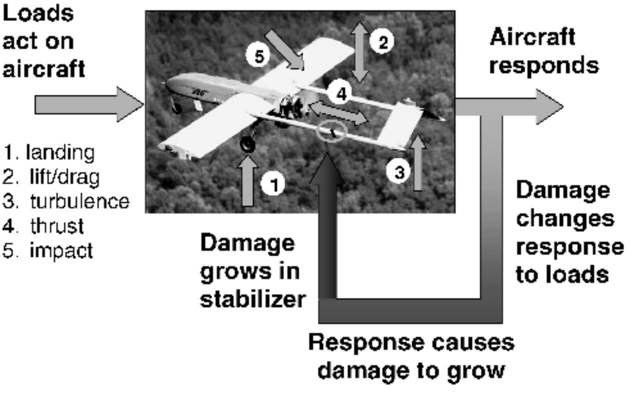

Figure 1.1 Aspects of health monitoring in an unmanned aerial vehicle

cracks or corrosion if the wing is metallic or matrix cracks, delaminations, or broken fibers if the wing is composite. Algorithms are needed to process the vibration data in order to assess the damage.

One key aspect to note in this example application is that when the aerodynamic loading on the stabilizer at location 3 is high, the crack in the strut affects the vibration response of the aircraft more than when the loads are low. *In other words, health monitoring technologies sometimes detect damage more readily when loads are acting on a component to accentuate the damage*. This aspect of health monitoring is one reason why monitoring may be preferred over inspections that are carried out offline (Hundhausen *et al*., 2004). In this case, offline inspections are performed on the ground when the aircraft is not operating. As the aircraft continues to respond, damage continues to grow in the strut, resulting in an ever changing load to the right side strut of the stabilizer. Damage grows in the future according to the current severity of damage and the nature of the loading applied to the component in the future. This aspect of damage accumulation in health monitoring is important because it results in a redistribution of the loads to or away from damaged areas (Haroon and Adams, 2005). *In other words, damage accumulation can result in changes to the way damaged components respond, suggesting that both the loading and damage should be monitored continuously in a system in order to predict the future operational capability of its various components*.

Models play a crucial role when loads are estimated, damage is identified and the future performance of a component is predicted. For example, without first-principle physics-based models, it would be necessary to acquire response data for each type of damage at various damage levels in the UAV in order to quantify the damage level (i.e. length of crack in the strut). If models are used, damage can be quantified with relatively few datasets (Johnson *et al*., 2004). On the contrary, if a damage mechanism such as corrosion that was not modeled appears in a component such as the stabilizer strut, then the model developed for cracks would incorrectly quantify the damage. In these instances, the data that is acquired should be relied on more heavily than first-principle models. *In other words, there are cases in which health monitoring should be based more on first-principle models and other cases when health monitoring should be based more on data*. Usually, a combination of data-driven and physics-based approaches is most effective when developing health monitoring algorithms.

1.2 COMMERCIAL NEEDS FOR HEALTH MONITORING TECHNOLOGY

Commercial applications are driving the need for health monitoring technologies. For example, Figure 1.2(a) shows a large truck used at excavation sites for hauling debris. Manufacturers of products such as this truck are now leasing their products instead of selling them. This new business approach, which is similar to the one employed by rental car companies and is referred to as ‘power by the hour’, requires that manufacturers maintain the performance of their customer’s products in order to make a profit. For example, it is estimated that a 2 % increase in downtime per year for 20 of the trucks in Figure 1.2(a) would cost the manufacturer \$13 million.

Condition-based maintenance (CBM) is the application of health monitoring technologies for the purpose of scheduling service and maintenance for products according to the condition of those products as opposed to a fixed time table. For example, the operator’s manual for an automobile usually specifies that the car be serviced every 2000–3000 miles in the first few years of operation. However, the oil condition at 2000 miles might not warrant replacement, or in some cases, the suspension or battery might indicate that service is needed prior to 2000 miles. If service were scheduled when the oil begins to lose too much viscosity or the battery begins to lose charge, the car would operate more efficiently and would cost less to maintain in the long run. CBM would make it possible for manufacturers to service their products more efficiently in a timely manner to avoid catastrophic failures and delays. Manufacturers could also order parts just-in-time through autonomic logistics to avoid failure and downtime if health monitoring information were readily available.

CBM would also apply to gas turbine engines in commercial aircraft containing discs, rotors, bearings, wire harnesses (Figure 1.2(b)) and fuselage components. Health monitoring information could help to increase safety and reduce delays in air traffic. For example, in December 2005, an Alaska Airlines plane flight number 536 traveling from Seattle, WA, to Burbank, CA, was struck by a baggage cart prior to take off, but the operator failed to notify pilots. The plane lost pressure in the fuselage at 26 000 ft 20 min after taking off and was subsequently forced to make an

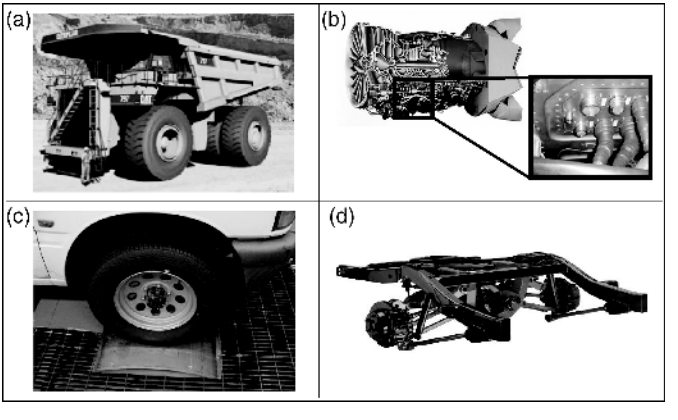

Figure 1.2 (a) Mining truck used for excavation (courtesy 2003 Pan American Damage Prognosis Workshop), (b) gas turbine engine with wire harnesses and connector panel, (c) radial tire subject to bead and tread damage, and (d) lightweight integrated truck suspension system with many components

emergency landing triggering major delays in regional air traffic. If effective health monitoring technologies had been installed on this aircraft, those technologies would have automatically notified crew about the impact, thereby helping to avoid the risk to passengers and travel delays.

In many other commercial applications, health monitoring technologies are affecting the development of products such as radial rubber tires (Figure 1.2(c)) and integrated suspension systems (Figure 1.2(d)). For example, tire recalls in 2000 focused national attention on tire regulations because the old standards from 1967 were written when 99 % of tires had bias plies. The US Congress responded to public concerns with the Transportation Recall Enhancement, Accountability and Documentation (TREAD) Act. Then the National Highway Traffic Safety Administration (NHTSA) issued new stringent requirements for tire durability with an emphasis on radial tires and bead area damage where the tire meets the rim. In tire fatigue endurance testing, health monitoring technologies for detecting bead area damage are needed to reduce the time and variation of manual inspections (Johnson and Adams, 2006). Centrifugal forces and heating from the rotation of the tire accentuate the effects that defects have on the tire response along the bead. These load interaction effects suggest that health monitoring techniques may be preferable to offline inspection methods for which these operational loads are not applied. Such technologies for reliability testing could also eventually be implemented in passenger cars and trucks to monitor tire health continuously.

Similarly, suspension systems in cars and trucks are being designed in new ways to reduce weight/cost and increase handling performance and reliability. Integrated suspension systems such as the one shown in Figure 1.2(d) are lighter, resulting in better fuel economy vehicles. The durability of integrated suspensions must be ensured through rigorous testing. Because these suspensions have many components and are geometrically complex, dynamic loads and mechanical damage in components are difficult to identify with traditional multibody modeling and manual inspection techniques (Haroon, 2007). Health monitoring technologies are needed to process the data acquired during these lengthy durability tests. Online data processing can quicken durability tests, making them less expensive for manufacturers.

1.3 DEFENSE NEEDS FOR HEALTH MONITORING TECHNOLOGY

This book focuses on health monitoring of structural components in commercial applications involving aircraft, ground vehicles, machinery and other types of mechanical systems. However, defense applications can also employ monitoring technology. For example, \$59 billion in maintenance costs made up 14 % of the US Department of Defense budget in 2004 (Navarra, 2004). In the US Air Force, costs to operate and support aging aircraft are rising and new procurements of modern aircraft are declining. If aircraft were serviced when needed based on the vehicle health and mission needs instead of at fixed intervals, the readiness of aircraft could be ensured and sustainment costs would drop. For example, the F-16 requires as many as 25 h of maintenance per flight hour (Malley, 2001). As aircraft such as the C-17 cargo plane shown in the top of Figure 1.3(a) are flown on new missions, there is a heightened need for health monitoring to ensure that new loads due to rough landing strips and environmental factors (e.g. sand and smoke) are considered. New aircraft will also benefit from health monitoring. For example, the morphing air vehicle shown in Figure 1.3(a) will be articulated in nature with numerous components all of which could become damaged. Health data concerning these aircraft could be used to determine if missions with a particular loading profile could be successfully performed.

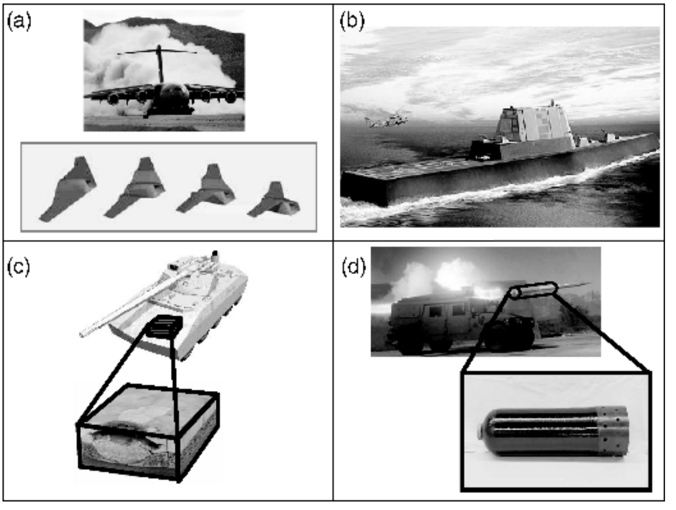

Figure 1.3 (a) Morphing aircraft design showing change in shape and C-17 aircraft landing on desert air strip with high loading to landing gear, (b) illustration of US Navy DDX destroyer, (c) lightweight composite armor and (d) composite missile casings

The US Navy also has an increased focus on mission readiness of their DDG class ships as well as their new DDX platforms shown in Figure 1.3(b). Ships contain the hull in addition to numerous hydraulic, mechanical and electrical subsystems, which enable vital functions from firefighting to propulsion. Knowledge of the hull and subsystem health prior to a mission could be used to determine if the ship's readiness is high enough to justify deployment. If health monitoring systems aboard the ship indicated that replacement parts are needed, then the ship could call ahead to the next available port to ensure that parts are delivered on time to enable repairs. This mode of operation where health monitoring systems are used to efficiently order parts is sometimes referred to as *autonomic logistics*. As the new DDX naval destroyer is designed and tested, health monitoring algorithms for processing thousands and perhaps millions of channels of sensor data must be written so that commanders can ascertain the capability of these ships prior to deployment and after deployment as the mission is updated to anticipate threats.

There are also needs for health monitoring technologies to ensure the readiness of defense systems used by the US Army. For example, new vehicle and body armors such as the materials shown in Figure 1.3(c) as well as new precision attack missiles composed of composite materials as shown in Figure 1.3(d) will be used in the future. In these new lighter weight defense systems, the Army Research Laboratory estimates that 85 % of all field damage is caused by some kind of impact event (Walsh *et al.*, 2005). Figure 1.4(a) illustrates a variety of transportation and storage-type incidents that can introduce impacts to missile containers. When impacts occur, there is a drop in burst strength of the composite missile casing as shown in Figure 1.4(b). By identifying the magnitudes of loads acting on these missiles, their ability to sustain a given firing pressure could be determined using this type of design data.

Ground vehicles present another interesting need for health monitoring because they are continuously being modified to combat new threats on the battlefield. For example, ground vehicles such as the one shown in Figure 1.5(a) experience large dynamic loads to the suspension. Additional weight due to armor and extra payload causes higher dynamic loading

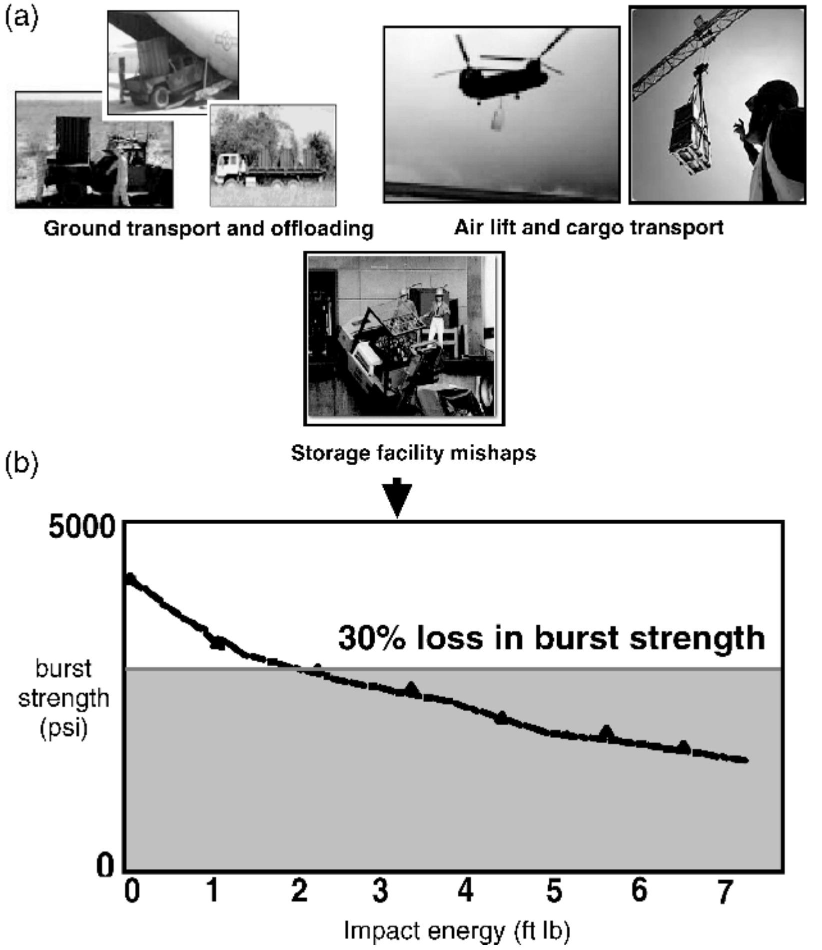

Figure 1.4 (a) Types of events that cause impacts of composite components and (b) typical loss in burst strength due to impact of missile composed of carbon filament (courtesy Walsh *et al*., 2005)

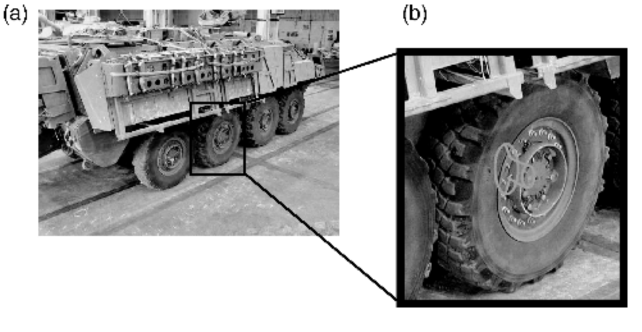

Figure 1.5 (a) Military ground vehicle and (b) spindle that experiences higher dynamic loading when slat armor is added to vehicle (Ackers *et al*., 2006, SPIE)

when the vehicle encounters rough terrain as drivers steer to avoid obstacles. These higher loads can cause damage in the drive train components such as the spindle shown in Figure 1.5(b). Changes in loading and any resulting damage in areas such as this spindle could be monitored to ensure the readiness of these vehicles. In many applications, the ability to monitor the performance of hard-to-reach areas such as drive train spindles, which cannot be accessed without tearing down the wheel, is the primary motivation for implementing health monitoring technology (Ackers *et al.*, 2006).

1.4 TECHNICAL APPROACH TO HEALTH MONITORING

Health monitoring technologies for systems such as the gas turbine engine wire harness and connector panel shown in Figure 1.2(b) involve four key elements as defined in Section 1.1: (a) loads identification, (b) damage identification, (c) damage growth prediction and (d) prediction of the effects of damage growth on component (or system) performance. Figure 1.6

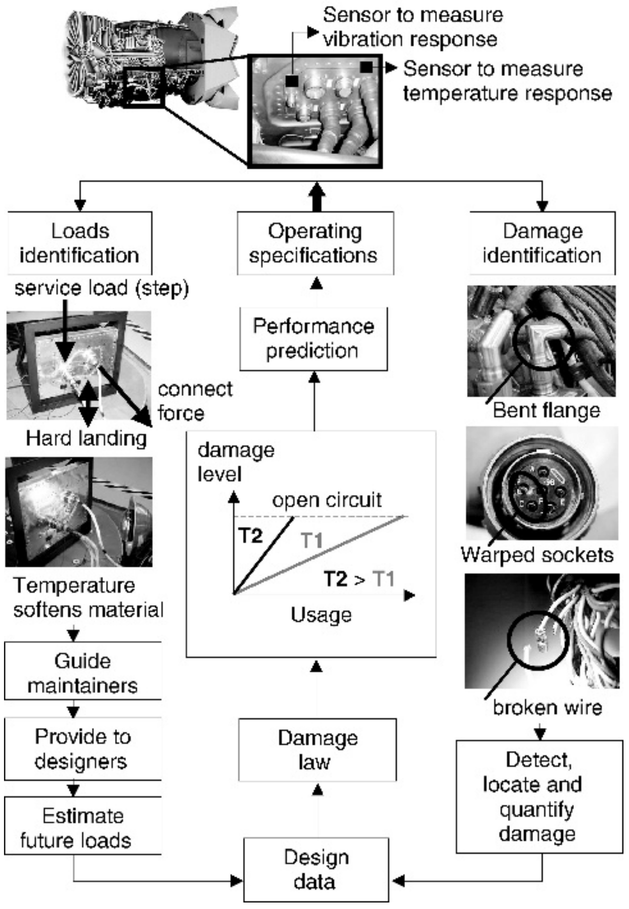

Figure 1.6 Health monitoring architecture consisting of loads identification, damage identification (diagnostics), damage and performance prediction (prognostics) for gas turbine engine wire harness and connectors

presents a health monitoring architecture comprised of these four elements as they apply to harnesses and connectors. Wire harnesses and connectors are an ideal application for health monitoring because temperatures are low enough to enable sensing (150 °C) and the wire harness affects the performance of many other components in the engine (Stites *et al*., 2006). Various aspects of the architecture for health monitoring of wire harnesses and connectors are described next.

Sensing

The response of the wire harness and connector subsystem to operational and environmental loading inside the engine must be monitored either continuously or frequently enough to provide meaningful health data. For example, it might be sufficient to sample the temperature at a slow rate like once per minute; however, it would be necessary to sample the vibration much faster like once per millisecond. In many cases, sensors are already conveniently integrated into components by manufacturers. For example, temperature and vibration sensors (accelerometers) are found in different locations of the engine. However, if there are no models that relate measurements at these locations to the conditions on the connector panel or harness of interest, then new sensors could be added. Pre-existing sensors can also pose limitations in amplitude or sensitivity; new sensors would be required in this case.

Sensors can be *passive* in nature, as in the case of a temperature thermocouple. Sensors can also be *active* in nature, meaning that one device called an *actuator* could transmit an acoustic signal through the connector or harness, whereas a passive sensor could measure the response to that input signal. For example, a piezo-ceramic actuator could be driven with a voltage signal that produces an acoustic 'ping', which travels down a wire harness, and a second piezo-ceramic sensor could measure the response on the opposite end of the harness. The main advantage of active sensing is that the input amplitude, frequency and so on, to the sensor can be controlled leading to higher signal-to-noise ratios and more repeatable data.

Sensors for measuring one variable such as the shock response of a connector that occurs during a hard landing are also sensitive to other variables such as temperature, electromagnetic disturbances and so on. Sensors must be selected to minimize sensitivity to sources of variation and maximize sensitivity to the loading parameters and damage mechanisms of interest.

Loads identification

The integrated sensors described above are used to monitor the operational and environmental loads that act on the wire harnesses, connectors, and the wires and pins contained within. Loads illustrated in Figure 1.6 include the following: hard landing shock loads that pull down on the harness, causing stresses in the connector; impact loads due to engine technicians who inadvertently step on the connector in order to gain access to different areas of the engine for service and maintenance purposes; and outward pulling loads on the harness that stress the connector and potentially wires inside the harness during servicing. In this application, it is important to monitor continuously for these types of loads. Some of the loads occur when the engine is operating, whereas others occur during pre-flight and post-flight system checks.

In general, loads could be *cyclic* or *transient* in nature. For example, hard landings cause transient vertical loads on the harness, resulting in stresses to the connector threads and pins. On the contrary, steady operation of the engine causes cyclic stresses in the connector and its pins. Environmental loading can also cause substantial changes in the operational mechanical loads that are measured. For example, when temperatures inside the engine compartment increase, the connector stress relief apparatus and the connector panel soften. This softening of the material (decrease in elastic modulus) produces larger response amplitudes when loads act on the harness, resulting in larger stresses to the connector.

After identifying the magnitudes, frequency ranges and so on of these various types of loads using algorithms that process raw sensor data, the information obtained can be used for a variety of purposes. First, an unusually high force level on a connector could be reported to maintainers, who could then inspect that connector to ensure it is connected properly and that there are no broken pins causing open circuits. Second, data collected on loads during operation could be provided to designers, who could use this information to revise design specifications. For example, the shock spectrum on connectors in different locations could be revised in specifications so that suppliers could improve future designs of the connector stress relief. Third, load data from the past can be used to predict what the loads are likely to be in the future. This future loading information is then used to make damage and performance predictions.

Damage identification

The integrated sensors described above are also used to identify potential damage in the connector and harness. Damage identification is often referred to as *diagnostics* or *state awareness*. In this application, it is important to at least isolate damage (or *faults* as they are sometimes called) in the harness/connector, because otherwise components attached to the harness may be replaced unnecessarily. For example, if the bent flange in Figure 1.6 that is introduced when a technician inadvertently steps on it results in an open or intermittent circuit to a starting motor for the engine, then that motor might be removed and replaced mistakenly. In addition, there are many possible damage locations in the wire harness and connector subsystem, so an automated fault detection system would be desirable.

Damage identification consists of several steps including *signal processing* and *feature extraction*. Signal processing methods are applied to raw data that is acquired from the integrated sensors in order to produce valid information for diagnostics. For example, it might be convenient to transform time data acquired from vibration sensors on the connector panel into frequency data using Fourier analysis techniques (discussed later). Then this frequency data can be used to extract features, which relate to a model of the damage mechanism of interest. For example, a model of the connector and panel could indicate that a loose connector causes a shift in a vibration frequency of the panel. Then the feature of interest would be this frequency value.

One of the main challenges in damage detection is the variability caused by changes in operational and environmental loading and the resulting variations in features used for diagnostics. These variations can cause false positive or negative indications of damage (called *false alarms*), which should be minimized according to the end user's health monitoring specifications. For example, if it is essential to identify every instance of a potential failure in the harness/connector no matter how improbable, then diagnostic algorithms should be designed in that manner. When selecting signal processing and feature extraction methods in health monitoring algorithms, the extent to which these methods amplify or suppress sources of variability must be considered. For example, if changes in engine RPM and temperature cause unwanted changes in frequency data, then those areas of the dataset should be discarded when attempting to identify damage.

In addition to detecting the presence of damage, damage identification algorithms should ideally also provide an indication of the damage location and level. For example, a damage location algorithm for the connector panel such as the one at the top of Figure 1.6 should indicate which of the seven connectors shown is damaged. The task of damage location usually requires a model of the component and data from multiple sensors. Similarly, the task of damage quantification nearly always requires a physics-based model of the component. Also, damage is more quantifiable using active sensing where the sensor signals can be compared to a measured input signal as described above.

Damage identification information can then be provided to maintainers to trigger additional inspections, maintenance or orders for replacement parts. This information is also used in the subsequent damage and performance predictions.

Damage prediction

After the loading and damage information is obtained, this information can be combined using some sort of damage law to predict how quickly damage will accumulate in the future. Design data that indicates the types of materials involved, geometry of the parts and so on is always needed to carry out the damage prediction task. For example, design data might indicate that the flange shown in Figure 1.6 can sustain a certain amount of deformation before the wires snap against the sockets. A solid mechanics model of the flange could be combined with information about the current amount of deformation from previous loads. This updated model of the flange could then be used to predict the amount of time the connector could continue to operate with steady (cyclic) and transient loads anticipated in the future.

There are numerous types of damage laws for metallic, composite, ceramic and other materials. Each damage law (equation) is comprised of parameters that account for geometrical properties of the component (length, width, thickness) and loading characteristics (stress level, frequency, direction). In many cases, changes in damage can be predicted using trending models, which are based almost exclusively on previous loading data and trends in damage identification information. This kind of data-driven prediction works well if loads and the response behavior of the component in the future are very similar to those observed in the past. In other cases, changes in damage must be predicted using physics-based models that apply more broadly to different operational scenarios than those experienced in the past. For example, if the connector responds differently to small and large operating loads, then a physics-based model would be needed to describe changes in the bent flange for these different loading levels.

Performance prediction

The damage prediction law shown in Figure 1.6 (middle) illustrates that environmental factors also affect predictions. Two different curves are shown corresponding to a low-temperature case (T1) and a higher temperature case (T2). The usage of a component indicates the amount of time it has been operating or the number of loading cycles a component undergoes. The damage level is the prediction being made. When the damage level reaches a certain threshold, design data would be used to declare that the component has failed. In this case, failure would mean an open circuit might occur when the wires inside the connector bend and break. When it is predicted that the connector will fail if it continues to operate, this prediction is referred to as a performance prediction or a *prognosis*.

This performance prediction could then be utilized along with the operating specifications for the engine to determine if the connector should be replaced or can perform for a certain number of future flights. In addition, this information might be used to guide the crew who operate the aircraft and engine. For example, if the flange were in imminent danger of failing, then the pilots could be instructed to avoid hard landings, which might cause the flange to bend to the point where the wires break, and an open circuit condition is reached.

1.5 DEFINITIONS OF COMMON TERMINOLOGY

Health monitoring is an emerging field of engineering, but there is already a vast terminology associated with it. The first term that must be defined is *damage*. In this book, damage is defined as *a permanent change in the mechanical state of a structural material or component that could potentially affect its performance*. Common sources of damage in materials and structural components include the following:

Material examples:

Micro-structural defects (dislocations, voids, inclusions)
Oxidation/corrosion (loss of material)
Nitridation (build up of material)
Exfoliation (pealing)
Erosion (pitting, spalling, abrasive wear)
Yielding/creep (plasticity, loss in modulus)
Residual stress
Cracking (fatigue, matrix, ply)

Structural examples:

Fastening fault (weld crack, bolt preload, broken rivet)
Adhesive fault (de-bonding, delamination, separation)
Clearance change (gap)
Instability (thermo-mechanical buckling)

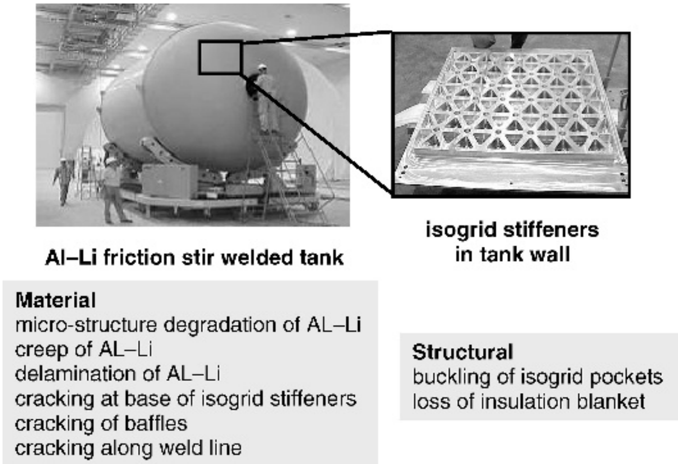

Figure 1.7 Types of damage in Al–Li friction stir welded tank (Ackers *et al.*, 2006, DEStech Publications, Inc.)

For illustration purposes, this definition of damage is applied below to an Al–Li cryo-tank, a thermal protection system panel and a large engine valve. First consider the large Al–Li tank shown in Figure 1.7. It is apparent from the picture of this tank that material and structural damage of the types listed could occur anywhere along the wall or dome. In fact, components such as this tank are called *unitized structures* because they do not use fasteners around which damage often localizes. Damage mechanisms such as these that can occur anywhere within a component are referred to as *global*. Global damage is difficult to detect and usually requires that sensors be distributed throughout the component. For example, acceleration sensors could be placed along and around the tank to measure different shapes in which the tank vibrates. In some cases, elastic waves can be propagated through the tank to detect damage with fewer sensor sets. This particular component is also said to be *damage intolerant* because even the smallest crack in the wall could be catastrophic due to pressurization of liquid fuel contained within the tank. The tank would be less sensitive to lost insulation, for example, over a short period of time during a launch if it became cracked in the location where insulation is lost.

Also note that large static acceleration forces (g forces) acting on the tank during launch cause inward or outward buckling of the tank. This buckling deformation causes relatively small defects in the wall to appear larger (open up) when health monitoring damage detection methods are applied (Sundararaman *et al.*, 2005). Recall that this type of change in how damage is perceived in sensor response data when components operate under load is one advantage of online damage detection techniques.

Next consider the metallic thermal protection system panel shown in Figure 1.8. This panel is a next-generation thermal barrier component with mechanical attachments, which are easier to install and repair, leading to faster turnaround times relative to the bonded ceramic tiles that are used in the Space Shuttle Orbiter (Hundhausen, 2004). Because this panel is constructed from multiple layers, it has damage mechanisms at the interfaces of all its subcomponents. For example, the face sheets (top and bottom) can debond from the honeycomb core. Components such as this panel are sometimes referred to as *parasitic* because they are attached to other structures.

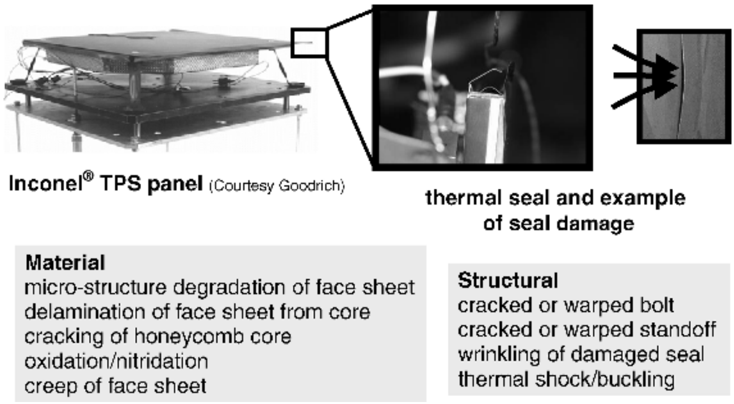

Figure 1.8 Types of damage in Inconel® thermal protection system panel

Damage mechanisms are often more localized in predetermined locations in parasitic components. For example, fasteners (bolts) can crack as can the mechanical struts in this panel. As in the Al–Li tank structure, the thermal protection system panel exhibits a sensitivity to load during damage detection. When the panel is heated during operation to as high as 1500 °F surface temperatures, the face sheet softens and the temperature gradient across the panel causes bending moments to act on the attachment bolts. These bending moments can be quite high, leading to a greater sensitivity of vibration measurements to small losses in preload through the bolt due to cracking. On the contrary, these high temperatures and fluctuations in temperature can also cause false positive indications of damage. To avoid these false readings, a thermo-mechanical model of the panel must be used or baseline data must be acquired at various measured temperatures. This baseline information can then be used to distinguish between changes in the panel response due to damage and changes due to temperature fluctuations.

Finally consider the engine valve shown in Figure 1.9. This valve is positioned on the intake airline of a large marine diesel engine. The purpose of the valve is to close off the air supply to the engine in the event of a fire or other emergency situation. Loads that act on the valve include low-frequency vibrations on the order of several gs ($1g = 9.81$ m/s^2) due to the engine crankshaft rotation and temperatures as high as 120 °F. The valve is also adjacent to the turbocharger, which introduces higher frequency vibrations.

Each of these loads and their combined effects on the dynamic response of the valve will be discussed in more detail later in the book. Damage mechanisms that result from these loads include those listed in Figure 1.9. Note that the bushing shown in the figure is clearly damaged due to impacts that erode the material. Other not so obvious damage includes the solenoid, which loses its pull force capability as temperature increases, and the internal valve mechanisms, which fuse together in a cold welding (material transfer) process due to the vibrations introduced by the turbocharger. This latter example of damage demonstrates that damage and failure in a given component are often caused by subtle interactions within the system (McGee and Adams, 2002).

In some cases, this definition of damage may not fit the situation. For instance, manufacturing flaws, such as assembly errors in the thermal protection system panel or the heat-affected zone in a friction stir weld, could be considered damage. However, these flaws could also be

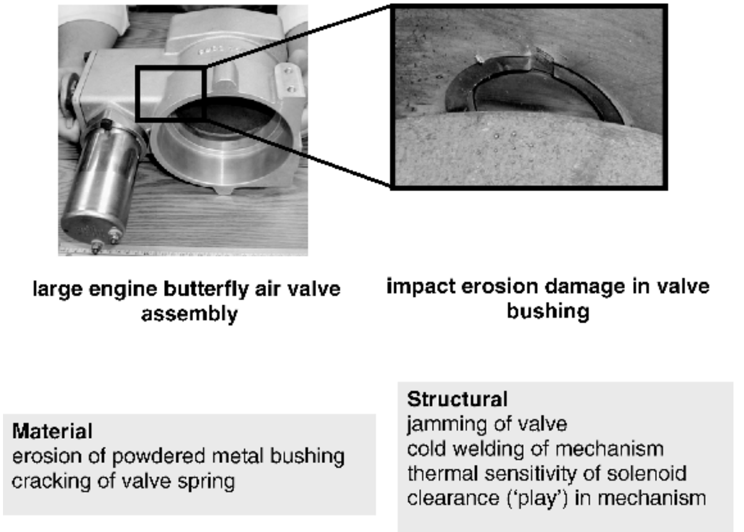

Figure 1.9 Types of damage in intake valve for large engine (Hundhausen *et al.*, 2005, John Wiley & Sons)

treated as part of the baseline (healthy) component. Squeaks and rattles in automobiles are less obvious examples of manufactured flaws. These sources of noise result in warranty claims to car companies and could be considered damage. However, it is customary to refer to manufacturing flaws as *functional degradation* if they affect performance but do not result in component failures.

In other cases, damage may be present but would not likely result in failure under ordinary types of loading. For example, a crack at the tip of a wing spar would not ordinarily be stressed to the point where it could cause structural failure of the spar. Similarly, the reinforced concrete support column shown in Figure 1.10 at the rear has experienced damage to the concrete due to high shear loading during the 1994 Northridge earthquake; however, the reinforcement bars in the column have not been damaged. This column might sustain traffic loads, which push down on the column. However, the damage the column has sustained might be sufficient to result in failure in the event of another earthquake so the column would be flagged as damaged in an inspection.

Figure 1.11 illustrates a generic example of this type of scenario where a component is damaged but does not lose its ability to perform under dynamic loading. In Figure 1.11(a), damage in the center mechanical element is not stressed during operation of the component, because the damaged area is not being strained. In this case, the damage could possibly be ignored for health monitoring purposes because the damage does not affect the performance of the component. On the contrary, this same damaged area is severely strained in Figure 1.11(b), resulting in a potential loss in performance under load. When defining damage in a given application, the nature of the operational and environmental loads must be considered.

Other commonly used terms in health monitoring are defined below. More terms will be defined as they are needed throughout the book.

Damage diagnosis: The process of identifying damage in structural materials and systems.

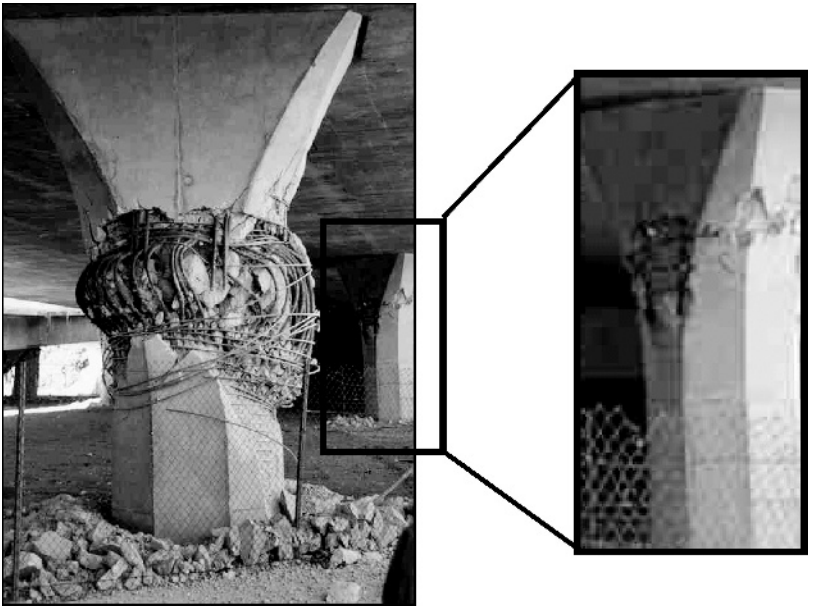

Figure 1.10 Damage to highway overpass reinforced support column during 1994 Northridge, CA, earthquake (courtesy Prof. F. Seible, University of California, San Diego) showing cracking in concrete of column in rear with less significant rebar damage

Damage prognosis: The process of predicting the future probable capability of a structural material or system in an online manner, taking into account the effects of damage accumulation and estimated future loading.

Failure: Instant at which a structural material or component has no remaining useful life.

Functional degradation: A reduction in performance of a component during operation that does not lead to failure.

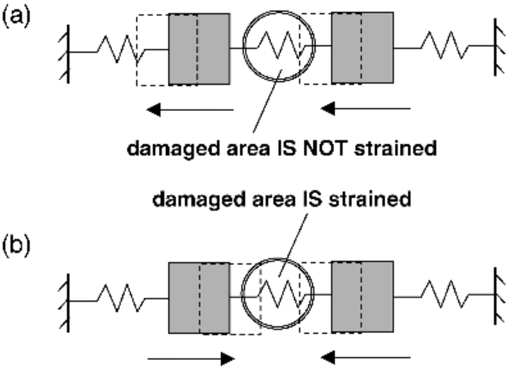

Figure 1.11 Damage in two different operating conditions: (a) damaged area is not strained by the motion and (b) damaged area is strained by the motion

Structural health monitoring (*SHM*): Health monitoring applied to structural systems in a variety of applications including mechanical, aerospace, civil, marine and agricultural systems.

Health and usage monitoring systems (*HUMS*): Same as health monitoring with application to rotorcraft and other types of machinery.

Integrated systems health management (*ISHM*): The process through which the operation of complete systems including mechanical, electrical, firmware and other subsystems are managed online using diagnostics and prognostics.

Integrated systems health monitoring: Health monitoring applied to any complete dynamic system such as an aircraft or ground vehicle system including all of its subsystems.

Intelligent maintenance: Same as condition-based maintenance where the condition of a structural material or system is used to schedule service and maintenance in an automated manner.

Nondestructive evaluation (*NDE*): The process of assessing the current damage state of a structural material or component without accelerating the damage.

Prognostic health management (*PHM*): Logistic processes through which the operations of structural components are managed using diagnostics and prognostics.

Product life-cycle management (*PLM*): The use of diagnostics, prognostics and software tools to manage the development and operational phases of a component.

Reliability forecasting: The process of predicting the future probable capability of a structural material or component in an offline manner using damage and future loading information.

1.6 COMPARISON OF NONDESTRUCTIVE TESTING (NDT) AND HEALTH MONITORING TECHNIQUES

NDT is the offline implementation of NDE methodologies for assessing the damage state of a structural material or component without accelerating the damage. There are many methods for NDT including dye penetrant testing, modal testing, radiography, ultrasonics, infrared thermography, eddy current and X-ray tomography (Hellier, 2001; Grandt, 2004). Health monitoring and NDT methodologies are similar in many ways. Both methods seek to identify the damage state of a structural material or component; however, health monitoring does this online as a component operates and also identifies loading and applies prognosis to predict future performance.

Health monitoring should be viewed as a complementary method to available NDT methods, which can be used to corroborate health monitoring data and perform more precise inspections of local areas of a component. For example, if a health monitoring system identifies that the UAV in Figure 1.1 has cracking in the stabilizer strut when the plane is flying, then an NDT method such as ultrasonics could be used to identify an accurate measure of the crack depth when the plane is on the ground. NDT would be applied locally to the strut producing a clearer image of the crack length, orientation and so on. Health monitoring of the entire UAV would be applied globally, leading to better awareness of the plane's operational health but less precise damage information. A complete comparison of these two NDE technologies is illustrated in Figure 1.12.

As shown in Figure 1.12, both methods provide information to operators for structural control (real-time changes) and structural design (future modifications) to improve the performance of components even if they should become damaged. In fact, one of the

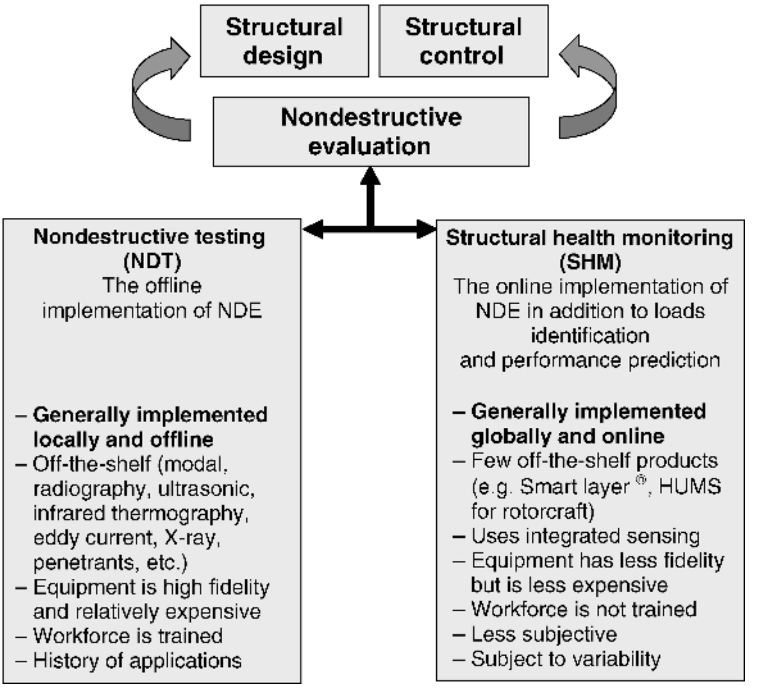

Figure 1.12 Comparison of NDT and health monitoring technologies

primary benefits of health monitoring technologies is that they can be used to optimize the weight, durability and other aspects of a component without sacrificing reliability.

For example, health monitoring data from the engine valve discussed in Figure 1.9 indicated that the valve could become damaged, resulting in a failure to close. This information was used to redesign the valve as shown in Figure 1.13. The new design was selected because it used a guillotine-type closure mechanism, which overcame the reduction in solenoid pulling

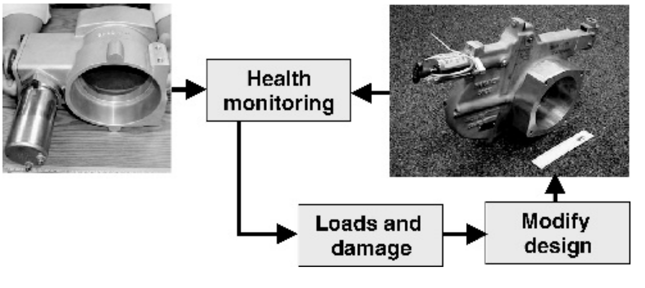

Figure 1.13 Previous generation engine valve and modified design with guillotine-type valve action to assist in valve closure

force with increases in temperature. The new design also avoided impacts that might hinder valve closure. Information about the vibration loading due to the valve position near the turbocharger also influenced future engine designs. This feedback of information about operational and environmental loading, damage and failure modes is an important role of health monitoring.

1.7 POTENTIAL IMPACT OF HEALTH MONITORING TECHNOLOGIES

Health monitoring technologies should not be applied in every application. Instead, six key factors should be evaluated before deciding that health monitoring approaches such as those presented in this book are appropriate. These factors are listed below along with examples taken from the structural components discussed earlier in the chapter.

Factor 1: Operational or environmental loading is highly variable.

- (a) When loads vary significantly, load interaction effects complicate the detection of damage using NDT (e.g. heating of thermal protection panel causes apparent damage level in cracked bolt to vary, Figure 1.8).
- (b) The growth of damage is also complicated by load interaction effects (e.g. transient overloads act on a cracked wheel axle in a mining truck, causing the crack tip to blunt followed by cyclic loads, Figure 1.2(a)).
- (c) The response of a structural material and component varies significantly, resulting in nonlinear, time-varying effects that complicate the health management of a component.

Factor 2: Loads, material, structural, damage or failure models are uncertain.

- (a) Complete usage databases do not exist for some new materials (e.g. filament wound carbon composites, Figure 1.3(d)) or structural concepts (e.g. morphing aircraft, Figure 1.3(a)).
- (b) Uncertainties in these areas can result in large health management uncertainties requiring some sort of diagnostic and prognostic information.

Factor 3: Designs are either significantly over or under conservative.

- (a) Health monitoring technologies can be used to assist in scaling back the weight in certain portions of the structural system (e.g. integrated suspension system, Figure 1.2(d)).
- (b) These technologies can also be used to manage risk in systems where lower factors of safety are used by necessity to enable operation (e.g. aircraft systems, spacecraft).

Factor 4: Systems are composed of many interconnected, interacting components.

- (a) Knowledge of more than one structural material or component is required in order to predict the performance of one particular component (e.g. integrated suspension system, Figure 1.2(d)).
- (b) Uncertainties in the interactions among these components lead to changes in system performance.

Factor 5: Unanticipated changes can occur over the system life cycle.
- (a) Health monitoring helps to manage risk due to structural modifications, inadvertent loads (e.g. service procedures as in the wire harness, Figure 1.6) and design or manufacturing flaws (e.g. rivet patterns that are skewed, leading to stress concentrations and cracking).

Factor 6: Damage can occur in hard-to-reach areas.
- (a) NDT methods cannot be applied to these areas unless the system is dismantled (e.g. wheel assembly in Figure 1.5 where spindle is buried).
- (b) Dismantling of a structural system can compromise its performance.

If these six factors are considered at a minimum and a health monitoring technology is implemented successfully, the end user of a structural system can realize some or all of the benefits illustrated in Figure 1.14. These potential benefits are described below with some examples.

(1) Reduced risk to operators and structural systems because of more accurate assessment of system health prior to operation (e.g. detecting cracks in Space Shuttle solid rocket boosters prior to launch).
(2) Performance optimization through prognostics-driven control (e.g. wear in satellite gyro bearings is opposed by adjusting the attitude of the satellite to redistribute lubricant around the bearings in order to reduce wear).
(3) Reduced risk through life-extending operation and control based on the use of health monitoring information (e.g. cracking in spindle of ground vehicle is identified and vehicle is removed from heavy service to avoid failure, Figure 1.5).
(4) Reduced cost for servicing structural systems and ordering parts (logistics) based on condition-based maintenance scheduling (e.g. damage in drive train or engine of mining truck is detected prior to failure and parts are pre-ordered to avoid costly

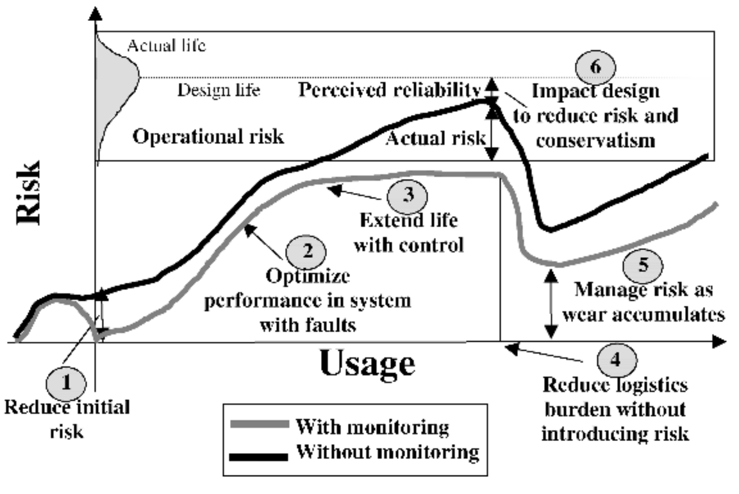

Figure 1.14 Benefits in system development, operation and renewal that can be realized using health monitoring technologies

downtime, Figure 1.2(a)). Asset availability may also be increased due to accurate estimation of remaining life and provisioning of just-in-time spares for field repair.

(5) Lower cumulative risk for sustaining the capability, or readiness, of a structural system after maintenance actions are taken (e.g. when wire harness and connector are serviced, there may be residual damage due to connection forces that bend pins over time or inadvertent impacts on connectors that cause damage to accumulate, Figure 1.6).

(6) Reduced design conservatism through online determination of future performance across a fleet of components or systems (e.g. missile casings are monitored throughout a military deployment and health monitoring data indicates that the weight could be reduced by removing layers of filament, Figure 1.3(d)). Traditional design approaches make conservative assumptions about the life across a fleet of components.

There are many health monitoring systems available for diagnosing faults in *rotating* systems. In some cases, these systems can be retrofitted to structural components to acquire and analyze data for health monitoring purposes. For example, consider the LANSHARC™ hardware (black box) shown in Figure 1.15(a) on the left. This system utilizes one vibration acceleration sensor placed on the nonrotating spindle housing of a lathe (shown in the right of Figure 1.15(a)). The acceleration data from this sensor is processed to calculate the value shown in Figure 1.15(b) as a function of part number. When the vibration level increases, this value increases. This particular machine would be taken out of service at 949 and 1600 cycles to replace the cutting tool. This kind of industrial machinery health monitoring system can save time and money by avoiding scrap parts and downtime in a production facility (Schiefer *et al.*, 2001). The system in Figure 1.15(a) is used in an automotive manufacturing facility.

There are fewer technologies commercially available for health monitoring of structural components. Consider the health monitoring technology illustrated in Figure 1.16. Figure 1.16(a) shows a planar component with an embedded SMART Layer® consisting of piezoelectric transducers that can transmit and receive elastic waves. This data is acquired and analyzed using a laptop computer and data acquisition system. Strips of the SMART Layer® can be installed in many different types of components. For example, Figure 1.16(b) shows a strip installed along a row of riveted joints around which cracks can develop and 'link up' causing fatigue failure of the aluminum lap joint. Figure 1.16(c) shows a small strip cut to fit an

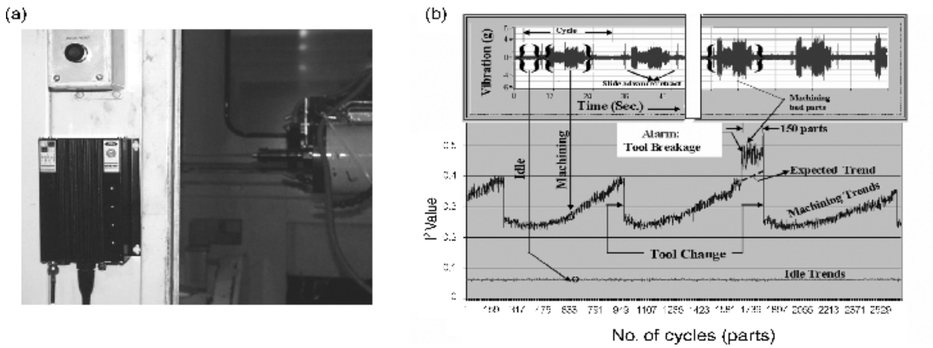

Figure 1.15 (a) LANSHARC™ condition-based maintenance system for monitoring spindle cutting tool and (b) unusual vibrations signatures indicate that tool needs to be replaced (Hundhausen *et al.*, 2005, Society for Experimental Mechanics, Inc.) (courtesy R. Bono, The Modal Shop Inc. of PCB Group, Cincinnati, OH)

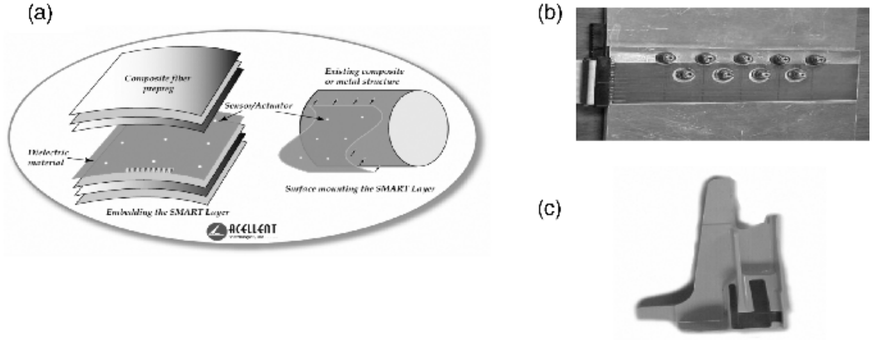

Figure 1.16 (a) SMART Layer® technology for embedding passive and active piezoelectric transducers into component, (b) panel with riveted joints around which cracks can develop and (c) landing gear with strips of sensors (courtesy Dr A. Kumar, Accelent Technologies Inc., Sunnyvale, CA)

aircraft landing gear part for health monitoring of loads and potential fatigue cracking in that component.

1.8 OVERVIEW OF TECHNICAL AREAS IN HEALTH MONITORING

The core technical areas of health monitoring discussed in this book include *modeling*, *measurements*, *data analysis* and *prediction*. These areas are broken down with subtasks in the flow chart shown in Figure 1.17. The first task in the flow chart is to define the health monitoring problem. The subtasks in the flow chart will be described in more detail in later sections of the book. A general point to note concerning these tasks is that they are interrelated. For example, models are developed for use in interrogating data and predicting performance. If models are not properly chosen to suppress sources of variability in measurement data, then damage will not be identified correctly.

To illustrate the interrelationships between the health monitoring technical areas, consider the thermal protection system example shown in Figure 1.18. In this system, models must be selected to describe panel damage such as a cracked bolt in the attachment strut. Models of the mechanical (vibration, acoustic) and environmental (temperature) loading applied to the panel must also be selected. These models are important because they are used in turn to select sensors, which can survive the temperatures behind the panel where sensors are installed. A typical launch vehicle would be covered with panels such as this one; therefore, it would be necessary to distribute sensors across the vehicle. With this distributed measurement network, models describing the panel loads would be even more critical for use in intelligently processing the measured data.

These models would be equally important for quantifying damage in the bolt (e.g. loss in preload) and accounting for sources of variability due to the thermo-mechanical loads. Variability affects both the sensor measurement and the computational algorithm used to interrogate data; therefore, steps to reduce this variability must be applied simultaneously in both the measurement and data analysis subtasks. Finally, the uncertainty in a prediction depends on the uncertainty in all preceding steps. By considering each of these technical elements in parallel, the propagation of uncertainty from element to element can be minimized in order to forecast crack growth in the bolt using the health monitoring models, data and features describing the bolt damage.

Finally, it is important to refer to the literature in health monitoring because there are continually new advancements in this field as technologies for sensing, computational mechanics and other areas emerge. There are numerous references available including those from the annual *Structural Health Monitoring International and European Workshops* (references given for 2004 and 2005 proceedings). The annual *SPIE Conference on Smart Structures and Nondestructive Evaluation* also publishes proceedings, which

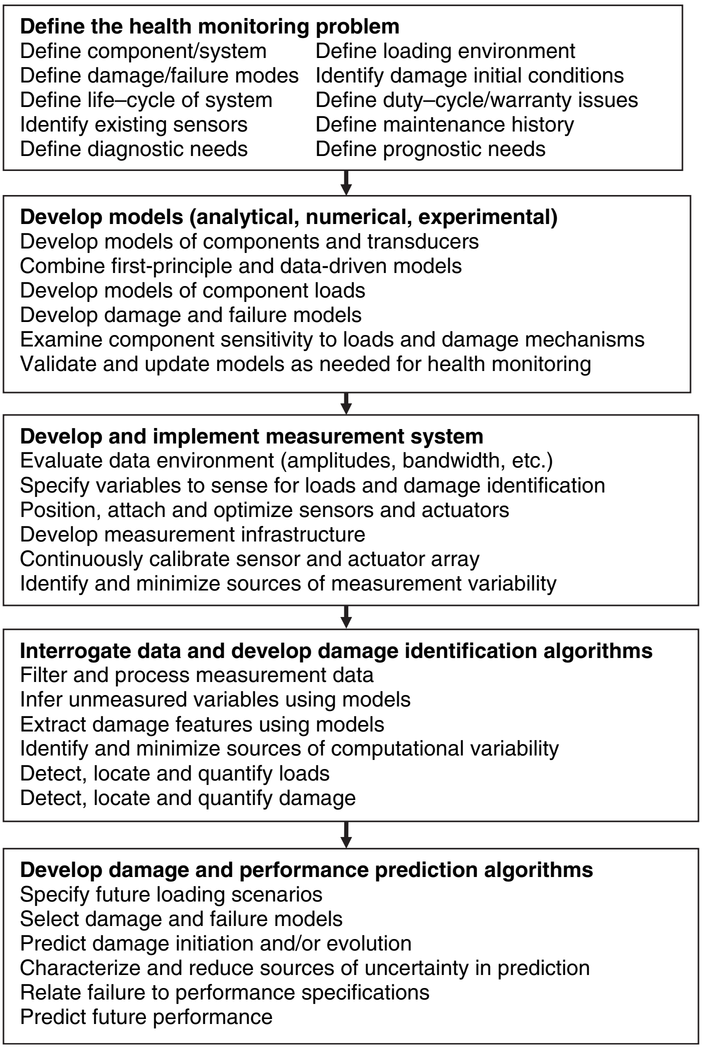

Figure 1.17 Flow chart of technical areas in health monitoring

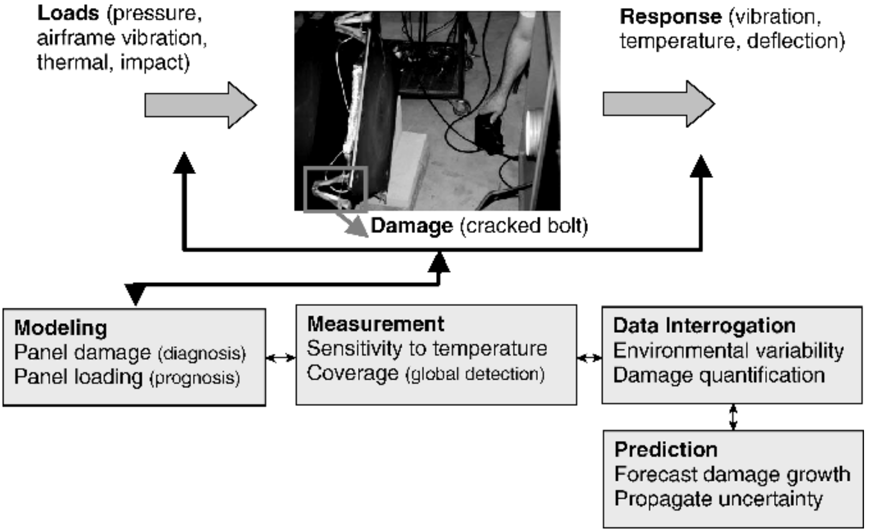

Figure 1.18 Interrelationships between technical areas of health monitoring for a metallic thermal protection system panel

contain a review of recent advancements in the field. Appendix B provides an overview of the technical journals and conferences that highlight developments in health monitoring. This book does not make an attempt to cover all of the methods available. Instead, examples are given of how to apply a basic methodology for health monitoring using vibration and wave propagation techniques involving the steps in Figure 1.17. Appendix B also provides a broad sampling of literature that focuses on many other health monitoring approaches.

1.9 SUMMARY

This chapter has defined the health monitoring process and technical elements involved in that process for a number of different applications. Key benefits of health monitoring were also discussed. A summary of key points in the chapter is given below.

- Health monitoring involves the *identification of operational and environmental loads*, *mechanical damage*, *the growth of damage*, *and the future performance of the component as damage accumulates*.
- Health monitoring technologies sometimes *detect damage more readily when loads are acting on a component to accentuate the damage*.
- *Damage accumulation can result in changes to the way damaged components respond*, *suggesting that both the loading and the damage should be monitored continuously* in the system in order to predict the future operational capability of its various components.

- There are cases in which health monitoring should be based more on *a priori models* and other cases when health monitoring should be based more on *data*.
- Health monitoring technologies can be used to implement *condition-based maintenance*, *which reduces the ownership costs for structural materials and systems*, and other business practices including autonomic logistics.
- Health monitoring diagnostic and prognostic approaches can be instrumental in product development for *identifying the durability of components and minimizing weight*.
- Sensing can be accomplished using *passive and active approaches*; passive approaches are relatively simple but more susceptible to measurement variability, and active approaches use actuation signals to better locate and quantify damage.
- The loads identification task can provide maintainers with information needed to service components or conduct additional *targeted inspections* in localized areas.
- Damage identification, also called *diagnostics*, aims to *detect*, *locate and quantify damage*; *signal processing and feature extraction* are two subtasks that require the use of models to distinguish damage from measurement variability, locate damage and quantify damage levels.
- Damage can be *local or global* in nature; local damage is restricted to a certain small region of a component, whereas global damage could occur anywhere in the component.
- Damage prediction, or *prognosis*, requires that damage laws be used; model-based prediction uses physics laws to forecast the growth of damage, whereas data-driven prediction uses trends to forecast the growth of damage.
- The term 'damage' is defined according to the *extent to which mechanical changes degrade the performance* of a component.
- Health monitoring and NDT are complementary technologies; NDT is implemented *offline and locally*, whereas health monitoring is implemented *online and globally.*
- Health monitoring has significant impacts on the *design and control* of structural systems in addition to the maintenance of those systems.
- Health monitoring should only be applied in cases where the investment in technology is justified for the reasons discussed in Section 1.7.
- Health monitoring involves *modeling*, *measurement*, *data analysis and prediction* tasks summarized in Figure 1.17.

The next two chapters discuss modeling and prediction techniques. Then issues in measurement methodologies and sensing technologies for health monitoring of structural materials and components are discussed in subsequent chapters. Data analysis issues are addressed for loads and damage identification. Then many of these techniques are applied to health monitoring case studies covering loads, damage and performance prediction in the final three chapters.

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PROBLEMS

(1) Consider the police ceramic body armor vest shown in Figure 1.19. List the potential operational and environmental loads that can produce damage in this armor. Also, list the likely damage mechanisms. What could loads identification information be used for in this

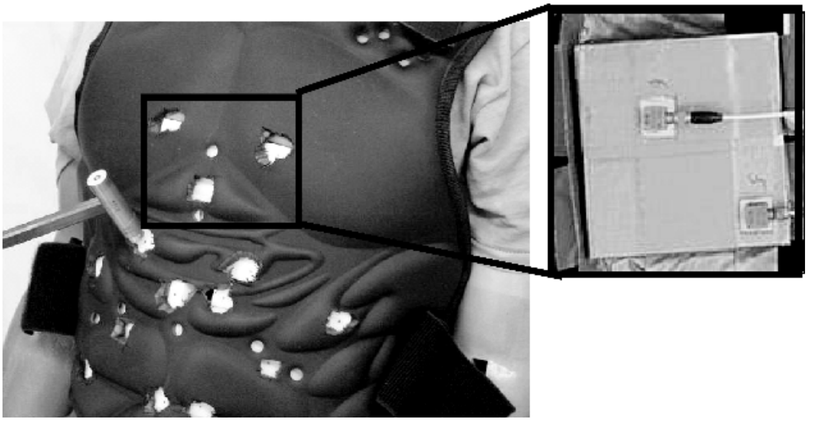

Figure 1.19 Ceramic body armor instrumented with response sensors

application? What about damage identification information? What would be the challenges in predicting the life of this armor?

(2) Consider the passenger truck shown in Figure 1.20. List the potential reasons from the list of factors in Section 1.7 that would justify the use of health monitoring in this application. Consider both consumer trucks and trucks used in commercial shipping businesses.

Figure 1.20 Passenger truck

(3) Read about one of the following NDT technologies in a reference and summarize the key advantages and disadvantages of those technologies: dye penetrant, ultrasonics, infrared thermography and radiography.

(4) Consider the rolling tire shown in Figure 1.21. Explain how a crack in the side of the tire changes as the tire is rolling. Include the effects of centrifugal forces, effects of tire tread deflection and temperature in your explanation.

(5) Consider the wrapped ceramic thermal protection system tile shown in Figure 1.22. It consists of a powdered ceramic core wrapped in a composite vest and is placed on a strain isolation pad, which is affixed to an aluminum airframe. List the potential operational and environmental loads that can produce damage in this tile. Also, list the likely damage mechanisms.

Figure 1.21 Rolling tire with bead damage

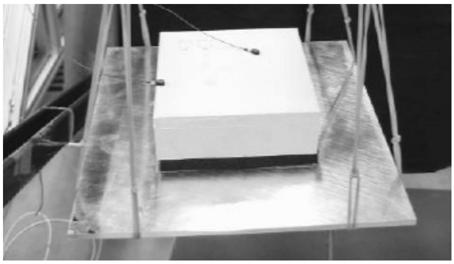

Figure 1.22 Wrapped ceramic tile bonded to aluminum plate

(6) Consider the windmill power generation system shown in Figure 1.23(a). List the potential operational and environmental loads that can produce damage in the rotor, transmission, electrical systems and tower (shown in Figure 1.23(b)). Also, list the likely damage mechanisms and examine the potential benefits of a health monitoring system for this application.

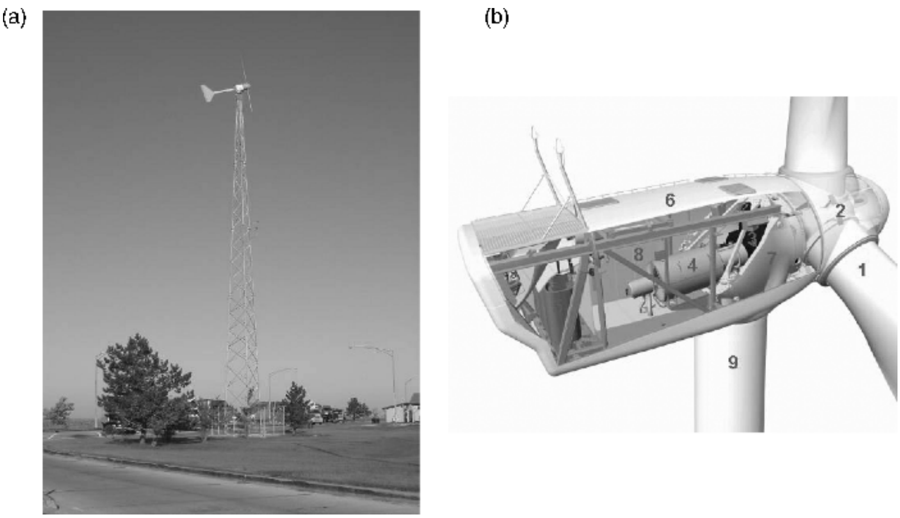

Figure 1.23 (a) Windmill station and (b) schematic of nacelle showing various electro-mechanical components