Adaptive Structures

Engineering Applications

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Preface

This book is based around the concept of 'adaptive structures', by which we mean engineering structures which have the ability to adapt, evolve or change their properties or behaviour in response to the environment around them. In recent years this concept has developed into a richly diverse area of research which includes topics such as structures, materials, dynamics, control, design and biological systems. The interdisciplinary fusion of these individual topic areas creates the possibility for new and exciting technological developments. These developments have been taking place in a wide range of industrial applications, but are particularly advanced in the aerospace and space technology sector.

Each chapter in this book represents the current state of the art in a particular aspect of adaptive structures, written by leading experts in their respective fields. But what about future developments beyond the current state of the art? Well, many chapters include discussions on future developments. More than this, we believe that by bringing together so many interrelated and yet diverse topics in a single volume one can get a sense of the huge future potential of this rapidly developing field of research. We hope that by viewing these combined chapters as a whole, the reader can enjoy the same sense of excitement and inspiration we felt when compiling this volume.

WHAT ARE ADAPTIVE STRUCTURES?

Humans have long been fascinated by nature's ability to build structures which adapt to their environment. In contrast, our own structures often appear inefficient, static and cumbersome. In engineering, the term 'adaptive structure' has come to mean any structure which can alter either its geometric form or material properties. These are processes which are currently much simpler than those which can be observed in nature. The terms 'smart', 'intelligent' and 'active' have all been applied to describe both materials and structures which exhibit some or all of these properties (see the selection of authored and edited texts referenced below). Increasingly, the ability to adapt to a performance demand or environmental conditions has become a key design criterion for a range of structural and mechanical systems in recent years. It is precisely this type of requirement which has become a key driver in the development of adaptive structure technology.

The adaptation process itself can be passive, active, based on material properties, control, mechanical actuation or some combination of these. As performance limits on structural systems are increasinlgly being pushed to more extreme levels, especially with respect to minimising weight, there is a strong requirement to find more efficient ways to apply adaption processes. This brings significant scientific challenges relating to structural stability, vibration, control/actuation, sensing and material behaviour.

There are many examples of adaptive structures from a broad range of engineering applications, but much of the driving force for development has come from the aerospace and space engineering sectors. The need for a high level of material performance in terms of strength, flexibility and minimal weight, coupled with the need for deployment and operation in extreme environments, has led to some of the most advanced adaptive structures currently in existence. There has also been considerable interest in new concepts such as 'morphing' wings for aircraft.

As these more advanced concepts of adaptive structures become realisable, the interaction and integration of material behaviour, control, sensing and actuation becomes ever more critical.

WHY ADAPTIVE STRUCTURES 2006?

This book forms a permanent record of the 2006 Colston Research Society Symposium on Adaptive Structures, held at the University of Bristol on 10–12 July 2006. The symposium formed part of of a wider celebration happening in Bristol during 2006 to mark the bicentenary of the birth of Isambard Kingdom Brunel (1806–1859), arguably the greatest engineer of all time. Brunel's influence on the science and application of engineering led to some of the greatest engineering achievements in history. The historic city of Bristol has special links to Brunel, with structures such as the Clifton Suspension Bridge and the SS *Great Britain* forming a prominent part of the city's engineering heritage.

Bristol retains a strong link with modern engineering as a key centre for European aerospace manufacture. Representatives from local industry took part in the symposium and a public lecture by Gordon McConnell, Senior Vice President – Engineering at Airbus UK, was given on 'Continuing the Vision – Airbus A380 and Beyond'. The focus of this symposium was to consider the direction and key challenges associated with the rapidly developing field of adaptive structures.

WHAT DID WE LEARN?

The book chapters stand alone in giving detailed information in specific topic areas. However, there are some strong 'emergent' or common themes which relate the diverse array of subject areas – from precise theoretical mechanics and control in piezoelectric devices, through advanced polymer chemistry, to the innermost workings of a Venus Fly Trap.

Firstly, it is clear that advanced material properties lie at the very heart of adaptive structures. In this book, topics covered range from chemistry to theoretical mechanics – seemingly disparate areas but crucial to the understanding of many problems. In fact this example highlights one of the key concepts to emerge from this book – integrated thinking. What do we mean by this? Any material has a chemical make-up and at the same time a mechanical behaviour. Our traditional approach to scientific research means that these two things are treated as completely separate subjects, so much so that many practitioners from either field may not even be able to communicate with each other! What is clear for adaptive structures research is that integrated understanding of a material's behaviour can lead to novel ways of exploitation.

This becomes more specific when we think about 'material' and 'structural' properties. Again, although often separated, throughout this book we see examples of 'multifunctionality' which makes this traditional separation irrelevant. In essence we need to see a blurring of the distinction between 'structure' and 'material', because when we do this new possibilities emerge which can potentially be exploited. This is often possible across the length scales. Although the dominant motivations are for aerospace and space applications (and a small amount of civil engineering) there are also many possibilities at the MEMS and nano scales.

Another common thread in this work is that of biological inspiration (or analogy/function). A clear message is that nature uses information and structure rather than energy to design its structures. Nature also makes significant use of hierarchy throughout its adaptive structures, leading quite naturally to multifunctional behaviour. It is also clear that with regard to obtaining information and acting upon it, our current sensing and control/actuation technology is some way behind that employed by nature. Again, we see that there is a strong driver towards integration of function – sensors which are also actuators, materials with integral sensors, etc. Structural health monitoring is relatively new in engineering, but an entirely natural (and essential) process for biological systems. Ways of efficiently closing the control loop to provide feedback continues to challenge our traditional engineering approach.

Imparting some degree of self-healing to an engineering structure/material is perhaps a prime example of how research is attempting to bridge the divide between the synthetic and organic. One can envisage such a functionality offering real benefit across a wide range of engineering applications; however, replicating the subtleties of the natural world continues to pose significant challenges.

Overall, there is a strong sense that we need to challenge existing ways of thinking: concepts, assumptions and design approaches. Throughout this book the reader will see examples of this type of new and questioning approach. But these thought processes are not just idle speculation – almost every one is backed up with high-quality experimental validation.

Arguably, had Brunel been alive today he would have been a champion of the thinking that is encapsulated within the work presented here. Never one to shy away from applying the latest technologies available, or indeed finding his own solutions to problems, Brunel would no doubt approve of the theme, topics and findings presented herein.

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Adaptive Structures for Structural Health Monitoring

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1.1 INTRODUCTION

For some time the adaptive structures community has focused on transducer effects, and the closest advance into actually having a structural system show signs of intelligence is to include adaptive control implemented with a smart material. Here we examine taking this a step further by combining embedded computing with a smart structural system in an attempt to form an autonomous sensor system. The focus here is based on an integrated structural health monitoring system that consists of a completely wireless, active sensor with embedded electronics, power and computing. Structural health monitoring is receiving increased attention in industrial sectors and in government regulatory agencies as a method of reducing maintenance costs and preventing disasters. Here we propose and discuss an integrated autonomous sensor 'patch' that contains the following key elements: sensing, energy harvesting from ambient vibration and temperature, energy storage, local computing/decision making, memory, actuation and

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wireless transmission. These elements should be autonomous, self-contained and unobtrusive compared to the system being monitored. Each of these elements is discussed as a part of an integrated system to be used in structural health monitoring applications.

In addition, the concept of using smart materials in a combined monitoring and self-healing function is briefly discussed. This chapter concludes with some thoughts on the way forward in monitoring which is a subset of the newly formed area called ‘autonomic structures’ and includes a short introduction to such systems.

Autonomous sensing requires the integration of a number of subsystems: power, sensor material, actuation material, energy management, telemetry and computing. This chapter discusses one such solution to building an autonomous sensing system as well as steps taken to further integrate such a system into a load-bearing adaptive structure. The basic idea of the autonomous sensing system proposed here is summarized in Figure 1.1.

The proposed sensing system must have the following components in order to function autonomously. First, it must be built around a transducer material that performs the basic sensing function. For the example discussed here, this material consists of a piezoceramic, which produces an electric field when strained (see, for instance, Dosch *et al.*, 1994). The electric field is then converted to a voltage, which is proportional to local strain and can be used to measure local displacement or velocity. Here, however, we are interested in measuring the electrical impedance of the sensing piezoceramic (PZT in this case) as discussed below. Figure 1.1 also indicates that the PZT serves as an actuator as well. Actuation is needed because many of

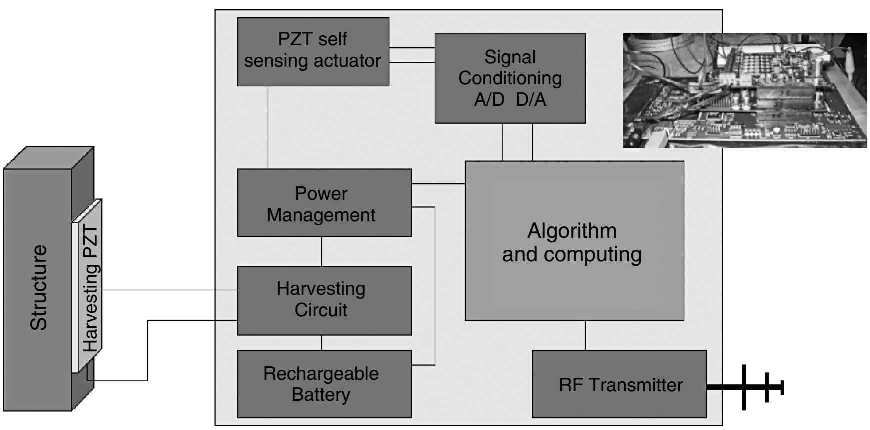

Figure 1.1 A proposed autonomous sensing system

the best algorithms for structural health monitoring (SHM) require a known input (Doebling *et al.*, 1998) in order to form measurements resembling a transfer function. At the very least, input–output measurements contain much more information than output only measurements. The existence of this actuation element separates the proposed active sensing system from many of the wireless sensing systems proposed by others (such as the Mote system). The circuit of Dosch *et al.* (1994) allows 'self-sensing actuation' and results in a reduction in the number of required components, reducing the size and weight requirements.

The second key element in the proposed autonomous sensing scheme is the use of a local computing platform. In a review of smart sensing technology for civil applications, smart sensors are defined as sensors which contain an onboard microprocessor giving the system intelligence capabilities (Spencer *et al.*, 2004). Several sensor platforms have incorporated microprocessors for the purpose of power management and signal conditioning using off-the-shelf chips. The system here takes the approach that (a) it takes less energy to compute than to transmit raw data, and (b) at some point during the sensor's life, it may be desirable to remotely change the algorithm used to determine damage. This is also the area in which further autonomy can be gained by enabling the sensor to make decisions. The philosophy of this approach is to make all the calculations at the sensor location and to broadcast only a limited amount of information in the form of a decision. Localized computing and decision again separates the proposed system from many of the previous efforts in the literature (Straser and Kiremidjian, 1998; Giurgiutiu and Zagrai, 2002; Lynch *et al.*, 2002, 2003). However, Lynch *et al.* (2004a, b) also use at-the-sensor computing to perform a time series analysis and broadcasts results, rather than raw data streams. A Berkeley–Mote platform is also used as a basis for a wireless structural health monitoring system with an embedded damage detection algorithm (Tanner *et al.*, 2003). A main difference between the approach presented here and other approaches is that they use a standard operating system whereas the goal here is to diminish the operating system to further reduce the power required to run the system.

The third key element of the system of Figure 1.1 is the power harvesting, management and storage system. Most systems to date use batteries as the source, and our goal here is to extend the autonomy of the sensor system by using various energy harvesting methods, power management and energy storage devices. The transmission device is taken as a standard off-the-shelf system here (see Lynch and Koh, 2005), and no new results are offered in the telemetry area. The main thrust of the work proposed here is to examine energy conservation through using a digital signal processor (DSP) platform without using an operating system (which tends to waste energy).

1.2 STRUCTURAL HEALTH MONITORING

Damage prognosis (DP) is the prediction in near real time of the remaining useful life of an engineered system given the measurement and assessment of its current damaged (or aged) state and accompanying predicted performance in anticipated future loading environments (Inman *et al.*, 2005). Self-healing can be thought of as structural repair of damage. A key element in damage prognosis and self-healing is obviously that of structural health monitoring (SHM). The added effort in damage prognosis is the concept of organizing the ability to make a decision based on the current assessment of damage by assuming future loads and predicting how the damaged system will behave. This prediction is then used to make a decision about how to use the damaged structure (or if to use it) going forward. A military aircraft hit by enemy fire gives a simple example of a prognosis system. The ideal prognosis system would detect the damage and inform the pilot if he/she should bail out, ignore the damage or perhaps continue to fly by under reduced flight performance. The battery indicator on a laptop performs a similar prediction in the sense that it measures current usage and estimates the remaining time left before required shutdown.

The added effort in self-healing is repairing the damage to return the structure to a usable state. A simple example is given below of a self-healing mechanism, while 'Self-healing composite materials' in dealt with in Chapter 9 of this volume. In the example given below of a self-healing bolted joint, there is a need to know the extent of the damage before self-repair can begin. Again, the concept of determining the state of the structure's health and the extent of its damage is a key element in the process. In this sense, damage prognosis and damage mitigation are natural extensions to SHM and can be viewed as the next steps.

In order of increasing difficulty, damage monitoring and prognosis problems can be categorized in the following stages of increasing difficulty:

1. Determining the existence of damage.
2. Determining the existence and location of damage.
3. Determining the existence, location and characterization (quantification) of damage.
4. All of the above and predicting the future behavior under various loads (damage prognosis).
5. All of the above and mitigating the effects of damage (self-healing structures).

6. Combining problems 1, 2, 3 or 4 with smart materials to form self-diagnosing Structures.
7. Combining the above with adaptive structures to form autonomous, self-repairing structures (autonomic structures).

Adaptive materials, or smart materials, and structures integrate very nicely into all seven of these problems. In the following, several examples are given to illustrate the effect that integrating these two disciplines has on solving problems arising in damage prognosis and mitigation, with the goal of eventually producing an entirely standalone chip fully integrated into a structure.

There are numerous SHM algorithms. A review of the SHM literature (Doebling *et al.*, 1998; Sohn *et al.*, 2003; Inman *et al.*, 2005) indicates that the main drawbacks and issues of the current SHM methods include:

1. *Spatial aliasing*: Conventional monitoring is accomplished with a limited number of sensors dispersed over a relatively large area of a structure providing poor spatial resolution and thus is only capable of detecting fairly significant damage.
2. *Cabling issues*: As a new generation of sensing technologies and sensor arrays pushes the limits of scale, the cabling and bookkeeping of sensor arrays has become an issue. Although wireless communication technology can provide a partial solution to this problem, *unwavering power supply to the transmitter remains largely unsolved*.
3. *Environmental issues*: Varying environmental and operational conditions produce changes in the system's dynamic response that can be easily mistaken for damage.
4. *Integration issues*: The predominant approach is to design separate systems leading to inefficiencies and reduced capabilities that could be increased through an integrated design philosophy.

Much activity has emerged in the area of wireless sensing (see, for instance, Lynch *et al.*, 2003). However, few have focused on the power requirements or on the integration of the algorithms into the choice of sensing hardware. In summary, the basic roadblock in adapting SHM methods in practice is that commercial sensing systems have not been developed with the intent of specifically addressing these drawbacks. The need to develop a system that goes beyond the laboratory demonstration and can be deployed in the field on real-world structures necessitates the goal of this effort: *that new sensing* *hardware must be developed in conjunction with software interrogation algorithms.*

The SHM algorithm used here is called the impedance method, was introduced by Liang *et al.* (1994), was used extensively over the last 10 years and is described next. Other algorithms, such as Lamb wave methods or vibration-based methods, can also be used, but, for the sake of simplicity and example, only impedance methods are discussed here.

1.3 IMPEDANCE-BASED HEALTH MONITORING

Impedance-based health monitoring techniques utilize small piezoceramic (PZT) patches attached to a structure as self-sensing actuators to simultaneously excite the structure with high-frequency excitations and monitor changes in the patch electrical impedance signature (Park *et al.*, 2003). Since the PZT is bonded directly to the structure of interest, it has been shown that the mechanical impedance of the structure is directly correlated with the electrical impedance of the PZT (Liang *et al.*, 1994). Thus, by observing the electrical impedance of the PZT, assessments can be made about the integrity of the mechanical structure.

The impedance-based health monitoring method is made possible through the use of piezoelectric patches bonded to the structure that act as both sensors and actuators on the system. When a piezoelectric is stressed, it produces an electric charge. Conversely, when an electric field is applied, the piezoelectric produces a mechanical strain. The patch is driven by a sinusoidal voltage sweep. Since the patch is bonded to the structure, the structure is deformed along with it and produces a local dynamic response to the vibration. The area one patch can excite depends on the structure and material. The response of the system is transferred back from the piezoelectric patch as an electrical response. The electrical response is then analyzed and, since the presence of damage causes the response of the system to change, damage is shown as a phase shift and/or magnitude change in the impedance.

The solution to the wave equation gives the following equation for electrical admittance as a function of the excitation frequency ω:

$$Y(\omega) = i\omega a\left(\bar{\varepsilon}_{33}^{T}(1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^{2}\hat{Y}_{xx}^{E}\right) \tag{1.1}$$

In Equation (1.1), Y is the electrical admittance (inverse of impedance), Z_a and Z_s are the PZT material's and the structure's mechanical impedances, respectively, Y_{xx}^{T} is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x