Smart Technologies *for* Safety Engineering

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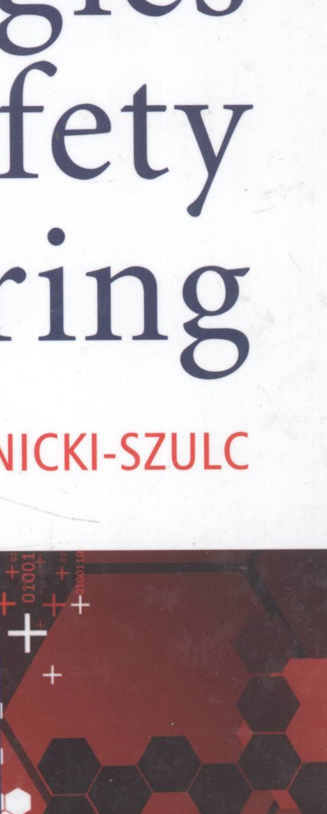

SMART TECHNOLOGIES FOR SAFETY ENGINEERING

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SMART TECHNOLOGIES FOR SAFETY ENGINEERING

Preface

The contents of this book cover the following research fields:

- new concepts of *smart technologies* and their applications;
- original methods and software tools for modeling, design, simulation and control of *adaptive structures*;
- application of the *smart-tech concept* to the following hot research topics and emerging engineering issues:
  - *health monitoring* of structures and engineering systems;
  - monitoring and *prediction of environmental conditions*;
  - automatic *structural adaptation* to unpredictable, randomly changing dynamic conditions;
  - *optimal design* of adaptive structures and engineering systems.

All of the above-mentioned topics are the key issues of *safety engineering*, encompassing automatic *damage identification*, unpredictable *impact identification* (e.g. due to automotive collision, earthquake or mine explosion) and real-time *mitigation of catastrophic impact* results.

Readers of this book are assumed to have the fundamental mathematical background of an engineer. Generally, the book addresses the system identification and control problems in various fields of engineering, e.g. aeronautical, aerospace, automotive, civil, mechanical and electrical. This book presents many different case studies to provide engineers with a comprehensive source of information on damage identification, impact load absorption and damping of vibrations. For example, automotive engineers designing a car bumper or civil engineers striving to construct safe bridges (monitored and impact-resistant) may find it useful.

About the Authors

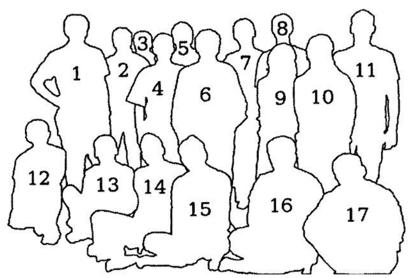
This book presents the research results obtained over the last decade by the Smart Technology Centre (STC), `http://smart.ippt.gov.pl/`, operating at the Institute of Fundamental Technological Research (IPPT) of the Polish Academy of Sciences (PAN), Warsaw, Poland. It collects achievements of several PhD theses, already completed or still being elaborated.

The STC is a division of IPPT-PAN, headed by Prof. *Jan Holnicki-Szulc*. He graduated from the Warsaw University of Technology in Civil Engineering (1969) and simultaneously from the University of Warsaw in Mathematics (1972). His PhD thesis (1973) and the habilitation thesis (1983) were defended in IPPT. He spent about 5 years (in the 1980s and 1990s) visiting various research labs in the USA, France, Spain, Portugal and Mexico. In the middle of the 1990s, he started to build the STC research group at IPPT-PAN, taking advantage of the fact that Polish labs became eligible for financial support through the European research initiatives, i.e. the 4th, 5th and 6th Framework Programmes.

The first PhD thesis in the STC was defended by *Przemysław Kołakowski* (1998) and devoted to the application of the *virtual distortion method* (VDM) to optimal structural remodeling, treated as a static problem. Then, one of the next theses by *Tomasz G. Zieliński* (2003) contained a generalization of the VDM for structural dynamics and its application to damage identification via the solution of an inverse problem. *Anita Orłowska* (2007) in her thesis developed an application of the dynamic VDM to the identification of delamination in composite beams. Further development of these numerical tools, allowing for fast and effective structural remodeling and solving coupled dynamic problems (including redistribution of material, stiffness and physical nonlinearity), was done by *Marcin Wikło* (thesis just completed). Dr *Łukasz Jankowski* (PhD defended in BAM, Berlin) and Dr *Bartłomiej Błachowski* (PhD defended in IPPT-PAN, Warsaw) joined the STC in 2005 and are both involved in dynamic load identification.

The further development of VDM applications to the structural health monitoring (SHM) concepts are under development in collaboration with the current PhD students *Andrzej Świercz* and *Marek Kokot* (theses almost completed). *Małgorzata Mróz* (thesis in progress) is working on the application of the VDM to optimal remodeling of damping properties in dynamically excited structures. Another group of PhD students, *Grzegorz Mikułowski* and *Piotr Pawłowski* (theses almost completed), *Cezary Graczykowski* and *Krzysztof Sekuła* (theses in progress), *Arkadiusz Mróz* and *Marian Ostrowski* (theses in progress), have already obtained interesting research results in the field of *adaptive impact absorption* (AIA). Finally, Dr *Jerzy Motylewski* is a key person in the STC in vibroacoustic measurement techniques and hardware development.

The team of seventeen co-authors is presented below; their contributions to particular chapters are listed in the *Organization of the Book*.



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6.	Jerzy Motylewski	Warsaw University of Technology, Electronics
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8.	Marek Kokot	Warsaw University of Technology, Mechatronics
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16.	Marian Ostrowski	Warsaw University of Technology, Mechanical Engineering
17.	Bartłomiej Błachowski	Gliwice University of Technology, Civil Engineering

The major research projects of the STC include:

- various national projects in the field of SHM and AIA
- UPWIND – Integrated Wind Turbine Design, FP6-2004-Energy-3, 2006–2011
- SAFE PIPES – Safety Assessment and Lifetime Management of Industrial Piping Systems, FP6-STRP-013898, 2005–2008
- ADLAND – Adaptive Landing Gears for Improved Impact Absorption, FP6-2002-Aero-1, 2003–2006
- SAMCO – Structural Assessment Monitoring and Control, FP5-G1RT-CT-2001-05040, 2002–2006
- SMART SYSTEMS – New Materials, Adaptive Systems and their Nonlinearities: Modeling, Control and Numerical Simulation, FP5-HPRN-CT-2002-00284, 2002–2006
- PIEZODIAGNOSTICS – Smart Structural Diagnostics using Piezo-Generated Elastic Waves, FP5-GRD1-2001-40589, 2002–2005
- COPERNICUS 263 – Feasibility Study on Active Track Support, FP4, 1995–1998
- COPERNICUS 150 – Design of Adaptive Offshore Structures under Extreme Wave Loading, FP4, 1995–1999
- NEXUSEAST – European Network of Excellence in Multifunctional Microsystems, FP4, 1994–1998

The major knowledge dissemination initiatives by the STC include:

- Smart Technology Expert Courses at IPPT-PAN (since 2003)
- European workshop on Structural Health Monitoring (co-organized with AGH, Kraków and IMP-PAN, Gdańsk), Kraków, 2008
- ECCOMAS Thematic Conference SMART'07 (co-organized with IMP-PAN, Gdańsk and IST, Lisbon), Gdańsk, 2007
- ECCOMAS Thematic Conference SMART'03, Jadwisin, 2003
- AMAS Course SMART'01, Warsaw, 2001
- NATO Advanced Research Workshop SMART'98, Pułtusk, 1998

Organization of the Book

The book has been divided into eight chapters, addressing the following problems:

- Chapter 1: **Introduction to Smart Technologies** (*J. Holnicki-Szulc, J. Motylewski and P. Kołakowski*) makes the reader briefly acquainted with some history and up-to-date trends in the fast-developing research field of Smart Technologies.
- Chapter 2: **The Virtual Distortion Method – A Versatile Reanalysis Tool** (*P. Kołakowski, M. Wikło and J. Holnicki-Szulc*) presents the basics of the method used by the authors for fast structural reanalysis. Both the static and dynamic analyses are included. The VDM-based sensitivity analysis, utilized in many subsequent chapters, is briefly announced. The versatility of the method, based on analogies between structural and nonstructural systems, is also discussed.
- Chapter 3: **VDM-Based Health Monitoring of Engineering Systems** (*P. Kołakowski, A. Świercz, A. Orłowska, M. Kokot and J. Holnicki-Szulc*) contains various applications of the VDM to the *structural health monitoring* (SHM) by solving inverse problems. First, the identification of stiffness and mass degradation in skeletal structures (both in the time and frequency domains) is discussed. Next, the very important engineering problem of the identification of delamination in composite beams (using the concept of a contact layer) is presented. Finally, two problems devoted to health monitoring of engineering systems (no longer structures) focus on leakage identification in water networks and defect identification in electrical circuits. The analogies between truss structures and other graph-modeled systems have been effectively used.
- Chapter 4: **Dynamic Load Monitoring** (*Ł. Jankowski, K. Sekuła, B.D. Błachowski, M. Wikło and J. Holnicki-Szulc*) contains research results for the problem formulated in two ways. First, on-line impact load identification is discussed as a crucial issue for *adaptive impact absorption* (AIA) systems, reacting in real time to the detected external loading. A fast response of the order of a few milliseconds is the main challenge for these systems. The second problem is related to the off-line reconstruction of an impact scenario on the basis of stored measurements of the structural response. This 'black-box' type of application is currently more frequently required in forensic engineering (e.g. in the reconstruction of transport collisions). The underlying methodology used in the second formulation is based on the VDM approach.

- Chapter 5: **Adaptive Impact Absorption** (*P. K. Pawłowski, G. Mikułowski, C. Graczykowski, M. Ostrowski, Ł. Jankowski and J. Holnicki-Szulc*) contains a description of the main AIA concept and its applications. First, the multifolding (*multifolding materials*, MFM) idea is demonstrated as a particular solution to the challenging problem of optimal topology design of AIA systems. Secondly, the problem of optimal adaptation (via the control of plastic-like stresses) of AIA systems to the identified impact is analysed. Inflatable structures with controlled release of pressure are discussed in a separate sub-chapter as a good example of AIA systems. Finally, application of the AIA concept to the design of adaptive landing gears and the related hardware issues are presented.
- Chapter 6: **VDM-Based Remodeling of Adaptive Structures Exposed to Impact Loads** (*M. Wikło, Ł. Jankowski, M. Mróz and J. Holnicki-Szulc*) presents the development of new, VDM-based numerical tools devoted to optimal design (or redesign) of AIA structures. This challenging objective requires special and original algorithms that can effectively solve the complex problem. The coupled analysis requires the plastic stress levels, element cross-sectional areas and mass distribution to be modified simultaneously. The AIA redesign tasks utilize the analytically calculated, VDM-based sensitivities, which are further employed in gradient-based optimization techniques. Remodeling of damping properties is discussed in a separate subchapter.
- Chapter 7: **Adaptive Damping of Vibration by the Pre-stress Accumulation Release Strategy** (*A. Mróz, A. Orłowska and J. Holnicki-Szulc*) presents the concept of the mentioned PAR strategy applied to adaptive damping of vibration. The effectiveness of the technique is demonstrated using smart devices able to control specially designed structural connections by switching them off and instantly back on. This semi-active approach is able to damp very effectively first modes of vibrations, transferring part of the energy to higher modes, with higher natural damping. Numerical results are presented and verified experimentally using a specially constructed demonstrator.
- Chapter 8: **Modeling and Analysis of Smart Technologies in Vibroacoustics** (*T. G. Zieliński*) discusses theoretical fundamentals of newly developed numerical tools necessary for accurate vibroacoustical modeling of structures or composites made up of poroelastic, elastic and (active) piezoelectric materials, coupled to an acoustic medium. A widespread design of such smart noise attenuators (absorbers and insulators) is still an open topic and should involve an accurate multiphysics approach. Modeling and analysis of smart multilayerd panels as well as of porous layers with mass inclusions improving the acoustic absorption are presented in the second part of the chapter.

Contents

1

Introduction to Smart Technologies

Jan Holnicki-Szulc, Jerzy Motylewski and Przemysław Kołakowski

1.1 Smart Technologies – 30 Years of History

The term *smart technologies* (Smart-Tech) is understood as a generalization of the concept of *smart structures*. Smart technologies encompass mechanical systems equipped with sensors, actuators and pre-programmed controllers, which allow a structure to adapt to unpredictable external loading conditions. The concept of smart technologies requires the knowledge about the mechanical system itself, embedded sensors and controllable devices (usually based on *smart materials*), and driving electronics with integrated software, which adds the *intelligence* to the system.

Technological developments in the field of smart materials (modifying their properties, e.g. due to variation of the electric or magnetic field) and computational techniques have reached a point in which their synergy has a significant impact on the applicability of the interdisciplinary concepts of smart technologies to real structures (*smart structures*). The material science has led to the theoretical and experimental development of multifunctional materials (e.g. piezoelectric ceramics, shape memory alloys, magnetorheological fluids (MRFs), magnetostrictive materials). Furthermore, the development of fast and miniaturized microprocessors has enabled the design of embedded systems with distributed control capabilities. The final integrated product is composed of the following items:

(1) a distributed sensing system (e.g. based on piezoelectric transducers) able to monitor the structural response;
(2) actuators (e.g. utilizing MRFs) able to modify structural properties and
(3) control units able to realize a pre-designed strategy.

Such systems can be very effective in many applications, including structural health monitoring, mechanical impact absorption, damping of vibration and noise reduction.

Intelligent structures became the object of scientific research (mainly as hypothetical solutions) as a result of new demands that came from the space engineering in the 1970s and 1980s. For example, the problem of shape preservation of a parabolic antenna, launched in space, is

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not a trivial task. The thermal shock that occurs while passing through the Earth's shadow can cause vibrations, which are very difficult to be damped. These vibrations are induced due to the high flexibility of space structures, resulting in their low natural damping. As a remedy, intelligent systems, able to mitigate these vibrations, had to be invented. This shape (and vibration) control problem can be formulated by making use of highly responsive piezo-sensors and piezo-based actuators. The above-mentioned shape control problem requires work to be done against the resisting structure, using actuators. In the case of large civil structures, this actuation leads to substantial energy consumption, which cannot be supplied instantly. Consequently, the applications for this type of smart structure are significantly limited. Nevertheless, an important class exists of large real structures that can be effectively controlled with smart devices, consuming little power. Such structures can be called *adaptive structures* (instead of *active structures*). They are equipped with the dissipative kind of actuators (or dissipators) only. The field of their application is, for instance, the *adaptive impact absorption* (AIA), in which a structure equipped with controllable dissipators has to absorb optimally the energy coming from external extreme loads.

In the 1990s, the smart structure concept was under development through various lab-scale demonstrations of fully active, but very flexible systems, dynamically controlled with piezo-patches. Adaptive (semi-active) systems were also applied effectively to very large real civil structures (e.g. tall buildings in seismic areas or suspension bridges with MRF-controlled dampers).

Currently, the main stream of worldwide research and development activities in the field of smart structures is focused on *structural health monitoring* (SHM) and *load identification* (mostly applied to civil, mechanical and aerospace structures). There are several periodically organized international conferences [1–5] and scientific journals devoted to the subject. These academia-industry meetings, gathering various engineering communities, demonstrate the rapid development of SHM hardware solutions, accompanied by a relatively slow progress of new software tools. Researchers do have access to huge databases collected via numerous installations (mostly the large bridges monitored in Japan and South Korea), but the *soft computing tools* (e.g. based on *neural networks* or *genetic algorithms*) seem to have encountered limitations in application to large real structures. The *structural control* is the second field of application for smart technologies (e.g. damping of vibration [6] in antiseismic structures or in suspension bridges by MRF dampers). Dedicated international conferences are periodically held on structural control [7, 8], including some SHM issues as well. There are also cyclic events strongly related to the SHM and structural control topics [9–13]. In general, the interdisciplinary solutions can provide some extraordinary properties, thus mechatronic ideas, for example, are more and more frequently applied in structural mechanics. Nevertheless, there are still new areas open to potential applications as well as possibilities of improvement in already existing solutions. An important example is the design of vehicles with improved *crashworthiness*. For example, new euro codes, imposing high survivability requirements in crash scenarios, are under preparation. An increased interest can therefore be expected in the development of effective methods (including hardware devices and software tools) for the design of safe, crash-resistant vehicles.

New, emerging areas for the application of smart technologies are autonomous systems able to:

- monitor environmental conditions;
- identify extreme loads in real time;
- adapt to overloading by proper tuning of controllable dissipators;