Chapter 1. Introduction to Optimization and Identification Techniques for Model-Based and Signal-Based Inverse Problems

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Introduction to Optimization and Identification Techniques for Model-Based and Signal-Based Inverse Problems

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Abstract

This chapter presents an overview of the Book Series in Direct Methods, Inverse Methods and Uncertainty Modeling, with focus on its Volume I: Model-Based and Signal-Based Inverse Methods, and includes an introduction to the different topics in Optimization and Identification Techniques comprising the several chapters included in this Volume I of the Book series.

1 Book Series in Discrete Models, Inverse Methods, & Uncertainty Modeling in Structural Integrity: overview

The Book series in "Discrete Models, Inverse Methods, & Uncertainty Modeling in Structural Integrity" is an initiative of the Post-Graduate Program - Integrity of Engineering Materials (PPG-Integridade) of University of Brasilia (UnB), organized as a collaborative work involving researchers, engineers, scholars, from several institutions, universities, industry, recognized both nationally and internationally.

This book series is an activity related to the Research, Development & Innovation (R,D&I) Project at UnB, titled: "Technological Demonstration Platform for Inverse Methods and Uncertainty Modeling Integrity of Structures and Components", available at the UnB Central Library (in Portuguese) (Jorge, 2020).

The Book Series project is comprised by three Volumes:

- Volume I – Model-based and Signal-Based Inverse Methods

- Volume II – Fundamental Concepts and Models for the Direct Problem
    - Part I - Material Modeling
    - Part II - Discrete Modeling

- Volume III – Uncertainty Modeling: Fundamental Concepts and Models

The different book chapters were elaborated encompassing the relevant project topics, including chapters covering:

- Fundamentals, including topics such as: basic principles, concepts & foundations, for the Direct & Inverse Problems (including model-based and signal-based inverse methods), and for the Modeling of Uncertainties;
- Special Topics, Applications, and Research Review, including topics such as: research review, state-of-the-art & future trend topics, for the Direct & Inverse Problems (including model-based and signal-based inverse methods), and for the Modeling of Uncertainties.

The different book chapters were prepared as a collaborative work by researchers, engineers, scholars, involved in research, development and applications in the related areas.

The research areas of interest throughout the book chapters include:

- Modeling of the inverse problem, monitoring & diagnosis / prognosis: models and methods for inverse problems, optimization methods (including techniques such as; multi-objective optimization, topology optimization, evolutionary optimization), Wavelets, Kalman Filter (KF), Particle Filter (PF), Machine Learning (ML), Artificial Intelligence (AI), Data Science (DS), for applications such as Structural Health Monitoring (SHM) (including impedance-based and Lamb Wave-based techniques), Health & Usage Monitoring Systems (HUMS);

- Modeling of the direct problem: mechanics of materials (including metallic materials, composites), structures (including civil, mechanical naval, aeronautical structures) machinery design and mechanical components, fracture mechanics, impact, fatigue, damage tolerance, integrity, mechanical vibrations, dynamics of structures, computational mechanics, including mathematical methods and numerical methods for discrete modeling for continuum mechanics (such as Finite Element Methods (FEM), Boundary Element Methods (BEM), Mesh-Free Methods (MFM));

- Probabilistic methods and modeling of uncertainties: probabilistic methods in engineering, Design of Experiments (DOE), Response Surface Methods (RSM), Risk & Reliability (including structural and system reliability), Uncertainty Modeling (UM) & Uncertainty Quantification (UQ), Bayesian Approaches (BA), stochastic Finite Element approaches (Stochastic FEM, Spectral FEM, Polynomial Chaos), sthochastic optimization, meta-modeling (including techniques such as Surrogate Models (SM), Reduced Order Models (ROM)), model Verification & Validation (V&V).

The different models, methods and approaches presented throughout the several chapters in the three Volumes of this Book Series are intended as an introductory presentation of some possibilities of methods that could be used in problems related to integrity of structures and components, and maybe even extended to other engineering areas, as appropriate. The list of models is not unique, and is neither comprehensive nor exhaustive, and the reader is encouraged to look for different possibilities of methods that may be applicable to the particular engineering problem at hand.

A common aphorism, often presented as *"All models are wrong, but some are useful"*, is usually considered to be applicable to scientific models in general, and to statistical models in particular. The aphorism recognizes that statistical or scientific models always fall short of the complexities of reality but can still be of use. The aphorism is generally attributed to the statistician George E. P. Box, although the underlying concept predates Box's writings.

The following sections present an introduction to Model-Based and Signal-Based Inverse Methods, with emphasis on the different topics in Optimization and Identification Techniques comprising the several chapters included in this Volume I of the Book Series, as well as their connection and relationship with regard to the whole setting of methods and models.

2 Volume I: Model-Based and Signal-Based Inverse Methods – context

The detection, localization, classification and identification of parameters and/or material properties, related to the integrity of structures and components, with and without defects or damages, involves the modeling of inverse problems, as well as an adequate modeling and quantification of the uncertainties involved in the problem.

The formulation of the direct problem, of the inverse problem, and the related uncertainties modeling, needed for an adequate description of the structure and/or the mechanical component, and of its potential defects or damages, involves multidisciplinary modeling techniques, whose understanding and proper application transcends the field of integrity and damage tolerance, being able to serve as a basis for applications, in other contexts or fields.

Among the application problems of interest for inverse methods, one can cite Structural health monitoring (SHM) and Health and Usage Monitoring Systems (HUMS).

The monitoring of structural integrity (SHM) is a competitive technique for damage detection and identification, wherein information is collected online, and compared with an existing database for an undamaged (“healthy”) structure. From this comparison, real-time information on the presence of damages can be obtained, including their localization, size, propagation speed, and, ultimately, the remaining operational life of the structural component.

The monitoring of mechanical components (HUMS) is a technique which is being used to follow / accompany the state of the integrity of mechanical systems / components (Health) and to monitor the appearance of indicators of the presence of damage (usage) in dynamic systems, such as rotating components (in engines, for example) and in gearboxes (in mechanical transmission systems, for example). In this case, the comparison is made between vibration signals from the healthy components (accumulated historical data) and from the components being monitored, to identify significant discrepancies in the vibration signals, which could be correlated to specific / particular / known damages.

The scientific challenge of the modeling of inverse problems, as well as of the adequate modeling and quantification of the related uncertainties, in a problem of integrity of structures and components, involves several aspects:

- The modeling of the problems (direct problem, inverse problem, uncertainties) needs to be done, whenever possible, by using more than one technique, for each case being described, in order to implement, for the particular problem at hand, model techiques which are independent, complementary, and/or redundant. Whenever possible, more than one model should be used, for redundancy and/or comparative analysis, especially in the case of unavailability of prior data for the healthy structure and/or component.

  The techniques used for inverse methods may involve:

  i. Optimization techniques, based on multiobjective optimization models, using classical optimization techniques (such as Sequential Quadratic Programming (SQP), BFGS, etc), or evolutionary optimization techniques (such as Genetic Algorithms (GA), Differential Evolution (DE), etc);

  ii. Identification techniques based on Artificial Intelligence, Machine Learning, Pattern Recognition, Data Science, etc, models (such as identification models based on Artificial Neural Networks (ANN), for example;

  iii. Models based on the Wavelet Transform (continuous Wavelet Transform (CWT), discrete Wavelet transform (DWT), with different types and sizes of the Wavelet window, for example);

  iv. Stochastic models (such as Kalman Filter (KF), Extended Kalman Filter (EKF), Extended Information Filter (EIF), Particle Filter (PF), Least Squares (LS), etc).

- In several situations, the direct models to be implemented may involve different problem physics (Multi-physics Modeling), and multiple scales (Multi-scale Modeling). In such cases, the description for the direct problem may involve coarser global models, and more detailed local models;
- The computational simulations and the experimental / laboratory tests must take into account the additional challenge of properly simulating / representing the local behavior of a complex structure, in the regions of interest, where the defect of damage is expected to be, or is expected to appear. For example, Fracture Mechanics (FM) problems and Damage Tolerance (DT) problems cannot be properly represented by reduced-scale models, as the damaged region must be represented using full-scale models. In these cases, the computational simulations (and also the experimental / laboratory tests) are required to reproduce the situation in the region of the damage using high fidelity local models. Thus, the region of the damage must be modeled in full scale, with the model also representing properly the geometry, the mechanical properties, and the real loading in that local region (loading that is coming from the external loads that were applied in the structure or in the component as a whole).
- In many cases, inverse problems may belong to the category of ill-posed problems, which represents an additional challenge in the modeling of the problem at hand. In these cases, the approach for the inverse method may require additional hypothesis to be made (for problem regularization, for example), or that a meta-modeling approach is adopted (such as surrogate models, reduced order models, etc), replacing the original model by the proper meta-model, and then solving this approximate model for the problem.

- The modeling of inverse problems, such as in the case of SHM and/or HUMS, must take into account the proper modeling of the sensor behavior, and also the uncertainties associated to these sensors, as well as the simultaneous use of multiple, independent, techniques for monitoring, with different sensors. The optimal sensor positioning, to maximize the Probability of Detection (PoD), may be seen as a topological optimization problem and/or as a stochastic optimization problem.
- The modeling of inverse problems may involve the detection, localization, and identification of parameters and/or material properties (for example, properties such as elasticity modulus, Poisson's coefficient, etc), which may vary through time (for example, material degradation thought time) and also along the length of the structure or mechanical component (for example, local changes which may occur in the material properties and / or mechanical properties of a composite plate, due to the debonding between the layers of the composite material).

3 Chapter topics in Volume I: Model-Based and Signal-Based Inverse Methods - presentation

Along this Volume I of the Book Series, several topics related to model-based and signal-based methods for inverse problems are presented in the several book chapters, representing the collaborative work from researchers, engineers, scholars, engaged in research, development and applications in the related areas, affiliated to several institutions, universities, industry, and recognized both nationally and internationally.

The book chapters in this Volume I of the Book Series are distributed as follows:

Chapter 1: Introduction to Optimization and Identification Techniques for Model-Based and Signal-Based Inverse Problems

Chapter 2: Overview of Some Optimization and Identification Techniques for Inverse Problems of Detection, Localization and Parameter Estimation

Chapter 3: An overview of Linear and Non-linear Programming methods for Structural Optimization

Chapter 4: Overview of Traditional and Recent Heuristic Optimization Methods

Chapter 5: Application of Machine Learning and Multi-Disciplinary/Multi-Objective Optimization Techniques for Conceptual Aircraft Design

Chapter 6: On a Bio-Inspired Method for Topology Optimization via Map L-Systems and Fractone Modeling

Chapter 7: Fundamentals on the Topological Derivative concept and its classical applications

Chapter 8: Ultrasound Obstacle Identification using the Boundary Element and Topological Derivative Methods

Chapter 9: Fundamental Concepts on Wavelet Transforms

Chapter 10: Application of Wavelet Transforms to Structural Damage Monitoring and Detection

Chapter 11: Inverse Methods using KF, EKF, EIF, PF, and LS Techniques for Detection, Localization, and Parameter Estimation

Chapter 12: Fundamental Concepts for Impedance-based Structural Health Monitoring

Chapter 13: Fundamental Concepts for Guided Lamb Wave-based Structural Health Monitoring

Chapter 14: Machine Learning and Pattern Recognition: Methods and Applications for Integrity Monitoring of Civil Engineering Structures

4 Final remarks and acknowledgements

This chapter presents an overview of the Book Series in Direct Methods, Inverse Methods and Uncertainty Modeling, with focus on its Volume I: Model-Based and Signal-Based Inverse Methods, and includes an introduction to the different topics in Optimization and Identification Techniques comprising the several chapters included in this Volume I of the Book series.

This book series is an initiative of the Graduate Program in Integrity of Engineering Materials (PPG-Integridade) at the University of Brasilia (UnB), Brazil (www.pgintegridade.unb.br).

The editors would like to thank PPG-Integridade and UnB for the initiative, incentive and support for this Book Series project.

The book series is organized as a collaborative work involving researchers, engineers, scholars, engaged in research, development and applications in the related areas, affiliated to several institutions, universities, industry, and recognized both nationally and internationally.

The editors are grateful and would like to show their appreciation to all the co-authors of the book chapters, for their participation, dedication, and support.

The book series is published as a digital version, with ISBN provided by UnB, and DOI for each chapter, provided by the Latin American Journal of Solids and Structures (LAJSS) (www.lajss.org). The scope of the Book series is in the broad areas of interest of LAJSS, and also of the Brazilian Society of Mechanical Sciences and Engineering (ABCM) (www.abcm.org.br) and the Brazilian Association of Computational Methods in Engineering (ABMEC) (www.abmec.org.br). For increased visibility, these three institutions are encouraging the divulgation of the Book Series project in their websites.

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