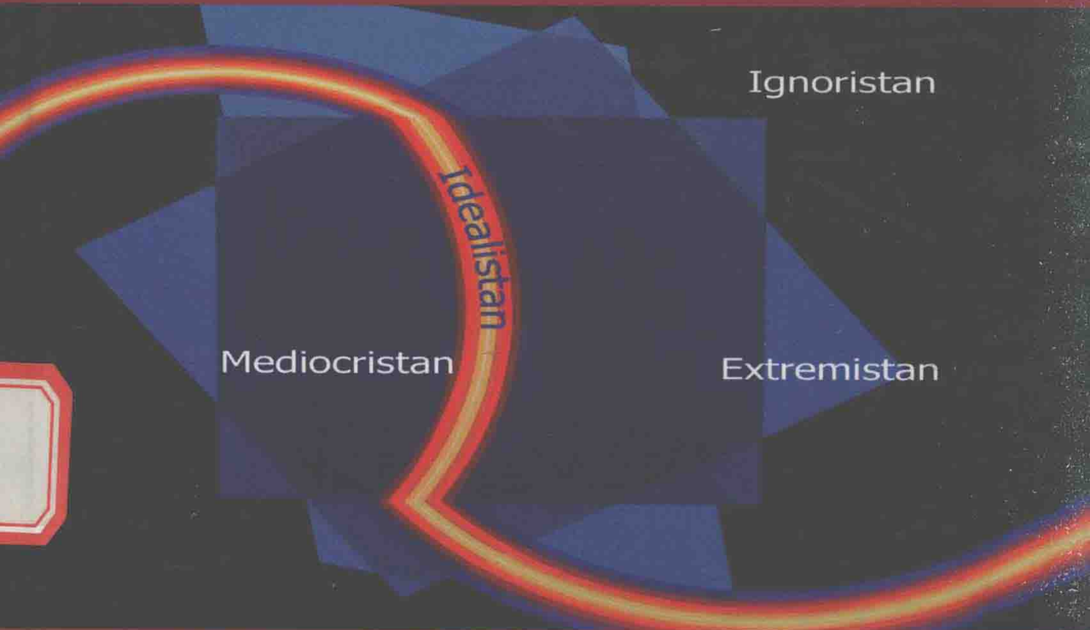
MECHANICAL ENGINEERING AND SOLID MECHANICS SERIES

Mechanics and Uncertainty

Maurice Lemaire



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Foreword

Industry requires innovation. Innovations are based on technologies, but while we often talk about product technologies (airplane, train, automobile, rocket, satellite, etc.), we rarely discuss the specific technologies involved in the design, testing and industrialization of these products, i.e. the skills involved in product development. This domain has undergone considerable progress in the past decade, with advances in modeling and simulation tools, highly instrumented tests and the use of supercomputers acting as motors for progress.

However, the complexity and multiplicity of the technical domains involved mean that the challenges of high-performance development, producing good results from the outset, are great indeed. Solutions must be found through the use of multiphysics, bringing together domains such as aerodynamics, solid mechanics, thermics and even acoustics. A statistical and probabilistic approach increases the reliability of results, and design methodologies are undergoing constant improvement, as demonstrated by current optimization applications.

The research aspect of design has undergone considerable progress in recent years. However, knowledge of the industrial skills and applications has not developed at the same speed. Significant developments have been made in process modeling for certain procedures, such as forging, casting and deep drawing, but significant work is still required in other domains, including machining, welding and surface treatments. Even more work will be required before suitable models are available for the whole routing for individual articles.

As vice president of the *Association Française de Mécanique* (AFM), French Mechanics Association, I launched a discussion of this situation with colleagues within the association in 2009. My basic premise was this: that while research aspects were undergoing rapid development, production planning was being left behind. We needed to find a way for the groups responsible for these aspects to work together to develop appropriate solutions. My colleagues at the AFM introduced me to a specialist in industrialization research, Régis Bigot, Professor at the Ecole Nationale Supérieure d'Arts and Métiers, Metz, who I met in 2009. We discussed the subject and its scientific and industrial implications at some length, identifying a number of researchers working in this domain from across France; we invited these experts to participate in a meeting at the *Maison de la Mécanique* mechanics center. To my surprise, our invitation was accepted by researchers from seven different laboratories (Metz, Bordeaux, Clermont-Ferrand, Mulhouse, Compiègne, Troyes and Valenciennes), and a number of intense and detailed discussions took place, finally leading to the creation of a focus group which continued to operate over the course of the following two years.

Through the initiative of Maurice Lemaire, a team, whose members are listed in the Preface, set to work on understanding uncertainty, describing the main modeling tools available and exploring the decision-making process as related to this context. The results of their observation are presented in this book, with the aim of guiding those who wish to contribute to develop knowledge and skills in the field of industrialization.

For me, three main points stood out from our meetings:

– We spent a full half-day session discussing the meaning and precise definitions of terms (notably "uncertain" and "uncertainty"); terminology definition is often an important step.

– An increasing awareness of the place of "uncertainty" in the technical domain: in terms of product development, mastery of uncertainty is lost wherever our knowledge of any aspect is incomplete.

– Finally, we were fortunate to be able to present our work to the wider mechanics community at the *Journée de l'AFM* conference in April 2010, a source of great satisfaction for a new cross-disciplinary group.

This book is the fruit of our reflection, and we hope for innovations that will provide new solutions in the complex domains of industrialization.

Jean-Marc THÉRET
President, AFM – 2010-2013
February 2014

Preface

The purpose of this preface is to provide readers with background information on the source of this book and to thank my colleagues involved in bringing this project to fruition.

This book is the result of an initiative launched by the *Association Française de Mécanique* (AFM), the French Mechanics Association. The AFM gathers those involved in the field of mechanics, based on three areas: science, technology and industry.

Over the centuries, mechanical science has developed through the construction of models, which, until the 19th Century, were thought to have considerable predictive validity, as seen in their application to celestial mechanics, where such models provide perfect results due to the infinitely small duration of observations in relation to cosmic time-scales. Later, the concept of perfect deterministic models began to break down, forcing researchers to take a scientific approach to uncertainty.

Mechanical technologies are the result of man's creative abilities, and are, to a certain extent, subject to chance, as their robustness and reliability can never be fully guaranteed. The performance of these technologies is therefore subject to uncertainty, and developers seek the best possible balance between the desired outcome and the cost of potential losses.

The mechanics industry implements technologies for design and production purposes. The design cycle, the production process and the life cycle of a product, as perceived by the user, are also subject to an environment for which the pre-existing information is incomplete. Uncertainty is also present in the components and systems of industrial projects. It can, additionally, come from the organization and its levels of resilience.

The first scientists to experience uncertainty in mechanics were undoubtedly those working on natural forces (such as earthquakes and storms), followed by those working on natural materials, such as soil. The awareness of uncertainty in structural mechanics and in design and production came later, and researchers needed to find ways to respond to the need for robust and reliable designs which go beyond the simple, but essential, manufacturing quality control.

Through the initiative of the AFM, I was invited to participate in a working group on "designing for robust production", led by Jean-Marc Théret and Régis Bigot, which brought together researchers from across the field of mechanics. The group identified vocabulary as a primary reason for uncertainty, both in methodology and in the description of objectives. For this reason, the decision was taken to create a document to precisely specify these concepts, introducing readers to a variety of methods, their strengths and their limitations. In the course of our discussions, participants were encouraged to explore and explain their thoughts in as much depth as possible, providing contributions that were then discussed and integrated into a homogeneous report.

I wish to thank these participants (in order of their appearance in the text):

– Jean-Yves Dantan for his remarks on sections 1.1.1 and 2.3.2.2.3, and his contribution to section 1.3, entitled *Designing for robust production*, through discussions with Régis Bigot and Alain Etienne.

Jean-Yves Dantan and Régis Bigot are Professors and Alain Etienne is an Assistant Professor at the Ecole Nationale Supérieure d'Arts et Métiers in Metz.

– Thierry Yalamas for his contributions to section 1.3.5.

Thierry Yalamas is an Associate Director of Phimeca Engineering S.A. in Paris.

– Nicolas Gayton for his contributions to discussions of section 1.2, entitled *Robustness and reliability*, section 1.3.3.1 concerning capabilities and contributions to the section on *Kriging* methods (i.e. section 2.3.3.2).

Nicolas Gayton is an Assistant Professor and research supervisor at the IFMA in Clermont-Ferrand.

– Sébastien Castric for his contribution to discussions of section 2.1.2.2 concerning *quantitative approaches to random uncertainty* and for his contribution to section 2.2, entitled *Uncertainty in behavior models.*

Dr. Sébastien Castric is a visiting researcher and Assistant Professor at the UTC in Compiègne. He has recently taken on training responsibilities for Airbus.

– Sébastien Berger for his contributions on *polynomial chaos*, sections 2.1.4 and 2.3.2.4.

Sébastien Berger is a Professor at the INSA's Val de Loire center in Blois.

– Felipe Aguirre for rereading section 2.1.2.2 on *quantitative approaches to random uncertainty* and sections 2.3.2.2.1 and 2.3.2.3 on *Possibilistic models*.

Dr. Felipe Aguirre is a research and development engineer at Phimeca Engineering S.A. in Paris.

– Cécile Mattrand for rereading section 2.2.2.5.1 *on Markov processes*.

Cécile Mattrand is an Assistant Professor at the IFMA, Clermont-Ferrand.

– Jean-Marc Bourinet for his contribution on *support vector machines (SVM)*, section 2.3.3.1.

Jean-Marc Bourinet is an Assistant Professor at the IFMA, Clermont-Ferrand.

– Vincent Dubourg for his contributions on *Kriging methods*, section 2.3.3.2.

Dr. Vincent Dubourg is a research and development engineer at Phimeca Engineering S.A. in Clermont-Ferrand.

– Jean-Luc Dulong for his contributions on the question of *model reduction*, section 2.3.4.

Jean-Luc Dulong is an Assistant Professor at the UTC, Compiègne.

– Yann Ledoux and Patrick Sébastian for their contributions to section 3.1, entitled *Decision support in design*.

Yann Ledoux is an Assistant Professor at the University of Bordeaux-1.

Patrick Sébastian is an Assistant Professor and research supervisor at the University of Bordeaux-1.

– Jean-Marc Théret for his contributions to the conclusion, section 3.2.1.2.6, concerning *the TRL scale*.

Jean-Marc Théret is the vice-president of Messier-Bugatti-Dowty, Paris.

The beginning of each contribution is indicated by a footnote and the end is marked by the symbol □ in the text.

I also wish to thank my colleague and friend André Lannoy of the Institut de Maîtrise des Risques (IMdR) for his valuable contributions in rereading and commenting on the preparatory document.

This list is not exhaustive, but it is sufficiently representative to show the conceptual and methodological aspects of uncertainty in mechanics. We hope that this book will help those involved in mastering uncertainty in mechanics to position their research and other activities within the broader, multidisciplinary context of the domain.

Maurice LEMAIRE
February 2014

Introduction

The title of this book "Mechanics and Uncertainty" joins these two terms, which are rarely encountered together. *Mechanics* is "a science, a technology and an industry" focusing on the study of movement, deformation and the states of equilibrium of systems. *Uncertainty* is a philosophical concept, often associated with questions concerning the nature of mankind and our destiny, but also with human creations. The convergence of science and uncertainty constitutes an acceptance of the impossibility of a deterministic predictive model, and our obligation to consider mechanical science in relation to uncertainty.

Here we will consider the history of our topic and the contributions made by a number of great thinkers, before providing a detailed overview of the contents of this book.

I.1. Mechanics and uncertainty throughout history

Confronted with the risks generated by natural disasters and by its own technical innovations, mankind began by turning to the gods. In 1722 BC, Hammurabi promulgated a code establishing sanctions of an eye for an eye, a tooth for a tooth in cases where users fell victim to construction faults. Over time, progress in reasoning, and in the calculation and observation of the natural world resulted in the replacement of the sanction principle by the idea of the predictability of events, modeled by mathematical algorithms, and the definition of their acceptability. In 1609, for example, Kepler published his famous set of laws establishing the elliptical trajectory of the planets around the Sun. In 1638, this was followed by Galileo's discourses on two new sciences, which constituted an introduction to modeling in mechanics. The success of these theories led many thinkers to believe that nature could be reduced to a set of mathematical expressions by the construction of increasingly precise models, and works continued in this regard until a point, at the end of the 19th Century, where science appeared to be more or less "finished".

Gerolamo Cardano (1501–1576), a renaissance mathematician, mechanical thinker and professional gambler, laid the foundations for probability theory in a book named *Liber de ludo aleae*. Later, Blaise Pascal discussed the role of chance in gambling in 1654, introducing the concept of chance as a factor in games: *when we work for tomorrow, and do so on an uncertainty, we act reasonably, for we ought to work for an uncertainty according to the doctrine of chance which has been demonstrated.* He invented the term *geometry of chance*, meaning that chance exists, but that it has a structure; this came to be known as the probability theory, i.e. proof theory, although it does not, technically, prove anything. As early as 1776, Buffon made the connection between statistics and reliability in considering the performance of wooden beams.

For mechanical engineers working in product design, the first of the two themes discussed above led to what may be called the *deterministic fallacy*. The second theme was largely ignored for many years, except in the creation of safety factors. Probability theory also introduced interpretation errors, or the *ludic fallacy*, as it only operates perfectly for games with perfectly defined rules.

At the beginning of the 20th Century, Henri Poincaré (*Sciences et Méthodes*, 1903) broke the deterministic certainties of models of the solar system, which had previously appeared to be perfect due to the infinitely short period of observation in relation to the real durations involved. The deterministic fallacy was demonstrated by the sensitivity of models to initial conditions: *a very small cause, which escapes us, produces a considerable effect that we cannot avoid seeing, and then we say that this effect is due to chance*. This reflection led to the idea of deterministic chaos, but Poincaré did not move outside of the framework established by Laplace: *nothing would be uncertain for an intelligence possessing perfect knowledge of all of the forces of nature*. Von Neumann and Wiener were the first to move beyond this limitation, with the idea of stochastic chaos. In engineering, the acceptance of chance, even framed chance, was subject to major opposition, as Le Chatelier declared in 1924 that *chance offers an escape route to the incompetent, who shy away from taking a scientific approach.*

However, engineers considering risk levels introduced statistical notions, following Mayer (1926) for construction, as part of the expertise process for design variables. A. Grenville Pugsley introduced a requirement concerning accident rates for aircraft in approximately 1930, and others, such as R. Lévi (1949) and A.-R. Rjanitzyne (1949), made use of the laws of probability. A.-M. Freudenthal (1949) *placed the concept of safety of structures in the realm of physical reality, where there are no absolutes and where knowledge is not perfect.* Noting the random distribution of initial defects, Weibull (1951) considered ruptures within a probabilistic framework, paving the way for the notion of mechanical reliability.

This context, coupled with the computing power now available to us, formed the basis of research activities in the second half of the 20th Century, leading to significant developments in probabilistic mechanics and its application to reliability and risk analysis. It also formed the basis for reflection by French engineers such as J.-C. Ligeron and C. Marcovici (1974) or A. Villemeur (1988), who considered ways of predicting the operational safety of electronic and mechanical components.

The work of A.-N. Kolmogorov (1903–1987) sparked the development of probability theory as a rigorous mathematical tool, which was then taken up by economists; however, the ludic fallacy is clearly visible in such cases, as the rules of the "game" are even less well known in economics than in mechanics.

The Mechanical Sciences and the Industrial Future of France (*Les sciences mécaniques et l'avenir industriel de la France*), published by the French *Académie des Sciences* in 1980 [INS 80], called for the creation of scientific teams bringing together experts in mechanics and probability. Thirty years later, the wishes of the *Académie des Sciences* have still not been completely fulfilled, and work is still required in this area; however, it is important to note that mechanics and probability alone are not sufficient. The issues involved in design, operation, maintenance and durability are subject to levels of uncertainty where probability alone cannot provide satisfactory responses in terms of risk management, whether in technical, economical or societal terms.

Mechanics and probability are clearly connected in the standard physical model, but this does not constitute an observational scale as required by the kind of mechanics discussed in this book. The question of the existence of chance is a matter for philosophical debate. In this case, we would do well to follow the ideas set out by Euler rather than Lagrange. In the context of the 21st Century, we are faced with a series of events that appear to be the result of chance, as it is impossible to reconstruct their trajectories. A scientific approach to uncertainty in mechanics needs to be developed.

I.2. Aims and outline of the book

Researchers are increasingly aware of the need to situate their work in an uncertain context, i.e. within a framework defining an imperfect knowledge frame, or, as Pascal put it, a geometry of chance. Technologies are never perfectly robust or reliable, and industrial products are subject to a variety of random situations both in creation and in implementation. Mathematical, physical, technological and industrial perspectives have led to the creation of a variety of methods and procedures, each contributing to a better understanding of uncertainty. The aim of this book is to summarize this information, enabling researchers to position each partial contribution within the broader scientific approach to mastering uncertainty.

For this reason, we will consider a large number of concepts, some at a relatively superficial level, highlighting their contributions and perspectives for implementation. The bibliography given for each point is not exhaustive; the main references will be cited, with a focus on French contributions, showing the richness of the work carried out at national level.

This book contains few mathematical demonstrations and is intended to provide an accessible starting point for scientists, engineers, industrialists and students interested in including aspects of uncertainty in their work; uncertainty is inherent to our world, and the consideration of this notion provides both strategic and operational benefits.

This book is divided into this Introduction and three chapters including eight sections, exploring uncertainty in mechanics following the order as shown in Figure I.1.

I.2.1. *Chapter 1: Understanding Uncertainty*

Developing an understanding of uncertainty involves consideration of three aspects: accepting uncertainty, defining measures and creating an approach to uncertainty.

– Section 1.1. (Uncertainty and reality):

This section will deal with historical considerations in greater detail and highlight the different ways of approaching uncertainty based on the available information, clearly showing the insufficiency of the probabilistic model.

Mechanics and Uncertainty - introduction

Chapter 1: Understanding Uncertainty

Section 1.1: Uncertainty and reality - Becoming aware of the uncertainty.

Section 1.2: Robustness and reliability - Defining uncertainty measures.

Section 1.3: Designing for robust production - Building a design process.

Chapter 2: Modeling Uncertainty

Section 2.1: Random uncertainty - Uncertainty modeling.

Section 2.2: Uncertainty in behavior models - Data and behavior models.

Section 2.3: Uncertainty propagation - Sensitivity and reliability.

Chapter 3: Decision Support under Uncertainty

Section 3.1: Decision support in design - Optimizing the balance.

Section 3.2: Summary and conclusion - Three points of view and challenges.

Figure I.1. *Exploring uncertainty: understanding, modeling and decision support*

– Section 1.2. (Robustness and reliability):

In this section, we will discuss the terms "robustness" and "reliability" – two facets of the same requirement for product quality – and the means of measuring these criteria.

– Section 1.3. (Designing for robust production):

This section analyzes the phases and steps in the design cycle and the approach to mastering robustness and reliability.

I.2.2. *Chapter 2: Modeling Uncertainty*

Uncertainty is modeled by representing data and behavior models and the propagation of data within models.

– Section 2.1. (Random uncertainty):

In this section, we examine the way in which knowledge is used to create representative models of uncertainty, from epistemic to aleatoric.

– Section 2.2. (Uncertainty in behavior models):

This section discusses the way in which data and behaviors are modeled.

– Section 2.3. (Uncertainty propagation):

This section details the propagation of uncertainty, in relation to the advancement of a project, for variables with or without measures of probability.

I.2.3. *Chapter 3: Decision Support under Uncertainty*

Decision support in the context of uncertainty necessitates compromises between design requirements and satisfaction for users, engineers and researchers.

– Section 3.1. (Decision support in design):

This section deals with the optimization of the balance between the contradictory constraints of industrial performance, robustness and reliability.

– Section 3.2. (Summary and conclusion):

In this section we will first provide a brief overview from the point of view of the users, the engineers and the researchers. We will then conclude with a discussion of different perspectives for the development of a science of uncertainty in engineering.

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