Rolf Steinbuch
Simon Gekeler *Editors*

Bionic Optimization in Structural Design

Stochastically Based Methods to Improve the Performance of Parts and Assemblies

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Preface

Bionics has become more and more popular during the last few decades. Many engineering problems are now solved by copying solutions found in nature. Especially the broad field of optimization has been inspired by the variety of methods to accomplish tasks that can be observed in nature. Popularly known examples include the strategies that ant colonies use to reduce their transport distances to feed their always hungry population, the dynamics of swarms of birds or fishes, and even replication of the brain's learning and adapting to different challenges.

Over more than a decade, we have been studying Bionic Optimization at the Reutlingen Research Institute (RRI). After early attempts to design optimization solutions using parameterized CAD-systems and evolutionary strategies, our field of interest became broader. Our work taught us how the different bionic optimization strategies might be applied, which strong points and which weaknesses they exhibited, and where they might be powerful and where inappropriate.

During a series of joint research projects with different partners and supported by the German government and other sponsors, we studied many aspects of these techniques. Additionally, the interest of the scientific community in Bionic Optimization is increasing along with the fuller understanding of how engineering can be influenced by non-deterministic phenomena. In this book we intend to give an introduction to the use of Bionic Optimization in structural design. Readers should be enabled to begin applying these nature inspired procedures. Furthermore, hints about the implementation, useful parameter combinations, and criteria to accelerate the processes are included.

To formulate most bionic optimization processes, scientists have attempted to base the strategies on a strong and reproducible theoretical foundation. On the other hand, most of these methods are so easy to understand that we realize they are working even if we decline to base them on a strict mathematical background. In this book we decided to explain the basic principles, show examples that are easy to understand, and list easily reproducible pseudocode to help new users to start working immediately. Comments on meaningful parameter combinations and warnings on problems and critical configurations may motivate readers to verify whether our proposals are justified, or if they can be expanded to broader regimes.

The work presented in this book mostly is a re-composition of different papers, theses, work reports, and presentations written throughout the last decade. The authors are former or current students at Reutlingen University, colleagues at the RRI, people who like working in Bionics, and young engineers who had, and have, plenty of ideas and are not too easily frustrated by flops. We have been following many tangents, have done thousands of studies, and have found solutions to many questions, but sometimes have failed to find the answers to others.

We begin with basic definitions and motivations, giving simple examples, and explaining how to set up an optimization environment. Some more elaborate applications then exhibit the power of these methods. Finally, a discussion about the future developments indicates how we expect optimization to be used in the future.

All this work would not have been possible without the support of many different sponsors. Besides the financial support of the German government in some research projects, many software companies and manufacturing enterprises gave us the opportunity to scan the wide range of bionic optimization in industry. We recognize their help, the fruitful discussions, and the generous handling of the licensing of the software packages. Additionally, we would like to express our gratitude to the heads of Reutlingen University, the RRI, and the faculty of engineering all of whom gave us access to space, time, and nearly endless computing power. We want to express our gratitude to Springer, especially Mrs. Eva Hestermann-Beyerle and her staff, who have helped so much to transform the collection of many different papers in different formats into one readable book.

Reutlingen, Germany — Simon Gekeler
April 2015 — Rolf Steinbuch

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About the Editors and Authors

About the Editors

Simon Gekeler, from Reutlingen, Germany, studied Mechanical Engineering at Reutlingen University and finished his Master thesis in 2012. While preparing his Master thesis and during the following years as a research assistant at Reutlingen Research Institute (RRI), he did research in methods of structural optimization, sensitivity analysis and evaluation of design robustness and design reliability.

Rolf Steinbuch, from Stuttgart, Germany, studied Mathematics and Physics at the University of Ulm. After 5 years with Siemens Power Stations, he moved to Mercedes-Benz. There he helped to introduce non-linear simulation into design processes. Since 1993 he is responsible for Numerical Structural Mechanics at Reutlingen University. His research focusses on optimization, acoustics and nonlinear problems.

Contributing Authors

Stephan Brieger, from Nürtingen, Germany, studied Mechanical Engineering at Reutlingen University and finished his Master thesis in 2006. While preparing his Master thesis and during the following 2 years as a research assistant at Reutlingen Research Institute (RRI), he did research in methods of structural optimization. Since 2009, he has been employed at Kolt Engineering in Böblingen as a Project Engineer, responsible for dynamics and vibration analysis.

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Nico Esslinger, from Oberndorf, Germany, finished his Master of Mechanical Engineering at Reutlingen University in 2015. Since 2014, he has been a research assistant at Reutlingen

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Christoph Widmann, from Reutlingen, Germany, studied Mechanical Engineering at Reutlingen University and finished his Masters thesis in 2012. During his thesis, he worked with the RRI specializing in Neural Nets. Since 2012, he has been working at WAFIOS AG in Reutlingen, where he is responsible for nonlinear dynamics, metal forming and vibration analysis.

Chapter 1
Motivation

Rolf Steinbuch

Since human beings started to work consciously with their environment, they have tried to improve the world they were living in. Early use of tools, increasing quality of these tools, use of new materials, fabrication of clay pots, and heat treatment of metals: all these were early steps of optimization. But even on lower levels of life than human beings or human society, we find optimization processes. The organization of a herd of buffalos to face their enemies, the coordinated strategies of these enemies to isolate some of the herd's members, and the organization of bird swarms on their long flights to their winter quarters: all these social interactions are optimized strategies of long learning processes, most of them the result of a kind of collective intelligence acquired during long selection periods.

1.1 A Short Historical Look at Optimization

In consequence it is not surprising to find optimization approaches in more highly organized human societies, focusing, for example, not only on the organization of social life but also on craftsmanship as well. Qualified professionals learn, try, fail, and improve until they are capable of performing their craft to certain perfection. And then new workers come, with the desire to surpass their antecessors, and create even better ideas and products. With increased productivity and the shorter lifetime cycles of industrial production, the need to deliver higher qualities in shorter times has become a continuous challenge. Today optimization is an inherent part of the industrial process. Since engineering, especially the design of machinery, started to

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become a discipline, more than merely an appendix of the manufacturing process, the task of optimization has been incorporated within its precincts.

1.1.1 Optimization in Engineering History

The founding days of Technical Mechanics, starting with the analysis of simple rods and beams, enabled engineers to predict the load carrying capability of a theoretical part and to select acceptable variants. At these early stages, an essential part of mechanical and civil engineering was devoted to finding methods, formulas, and predictions of the response of systems and structures. Engineers used these formulas to discover better solutions. Optimization might be regarded at least as one of the central items in mechanical engineering. Good engineers understand the processes they deal with, improve them, apply the relevant theoretical approaches, work out the essential consequences of the theory, and interpret them in an appropriate way. Following this approach, which is based on abstract thinking, the optimization is then transferred to the physical models. Through this process, engineers analyzed why the models did not work as expected, improved their understanding of the processes, and then designed new and better models. Parallel to this development, the efficiency of mathematical methods became more and more important. Among the central difficulties at that time was dealing with non-trivial formula, solving problems with more than two or three unknowns, studies of processes in time and space, and many other mathematical problems that required powerful handling of numerical tasks.

1.1.2 Finding Relevant Numbers in Engineering

Early on, finding the correct numbers for specific problems became a central challenge in the mathematical analysis of engineering problems, so there were many attempts to build calculators. Charles Babbage's difference engine and analytical engine, built at the beginning of the nineteenth century, was among the first and certainly among the most famous. But it was not until the 1930s that various developers, using electric current instead of mechanical contacts as leading technology, succeeded to produce relatively fast and reliable computers. The development of the transistor in the late 1940s allowed for the assembly of computers which were not built with relays or electronic valves and which were both very fast and very reliable compared to their predecessors. Up to today, we do not see any limits to the growing calculation capacity of these transistorized computers. In consequence, we are able to solve large problems with many unknowns in a short time, and this has caused Technical Mechanics to lose much of its frustrating aspects to engineers.

1.1.3 High Level Mechanical Methods

Parallel to the development of computers, new methods in mechanics arose. Beginning with early steps in the nineteenth century, Walter Ritz (1908) and Boris Galerkin (1915) proposed a method to solve structural problems that might be essentially more complex than the ones handled by the classical formula (Fig. 1.1). Richard Courant (c. 1923) was the first mathematician to understand the potential of their proposal, but development of these ideas was limited by lack of computing power. However, during the Second World War and in the years following it, scientists started to propose variants of these original ideas, which we know today as the Finite Element Method (FEM). Parallel to the FEM, the Boundary Element Method (BEM), often associated with Erich Trefftz, was developed and became an important tool in many engineering applications.

In the first years of use, the industrial application of both FEM and BEM was restricted to applications in which minimizing cost was a lower priority. So, air- and spacecraft, military weapons, nuclear industries, and some high level vehicle applications were using the then expensive numerical tools. In addition to the expense of computing power, up to the 1980s, the large effort to define and to enter the geometrical properties such as nodes and elements in FEM reduced the applications to simple problems and isolated studies. Consequently, in the early 1990s the meshing of a motor-head took about 6 months, not taking into account the other 6 months required to develop the wireframe CAD-model that served as basis for this FEM-model.

1.1.4 Drop of Hardware Costs and Better CAD Systems

In the 1990s two essential developments took place. 3D-CAD-Systems using solid models were developed. They required many fast and well performing local graphical systems be installed on powerful workstations. Since the workstations

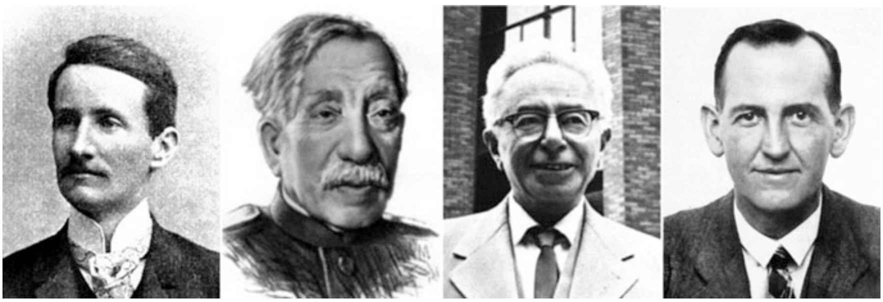

Fig. 1.1 Walter Ritz (Ritz), Boris Galerkin (Galerkin), Richard Courant (Courant), Erich Trefftz (Trefftz)

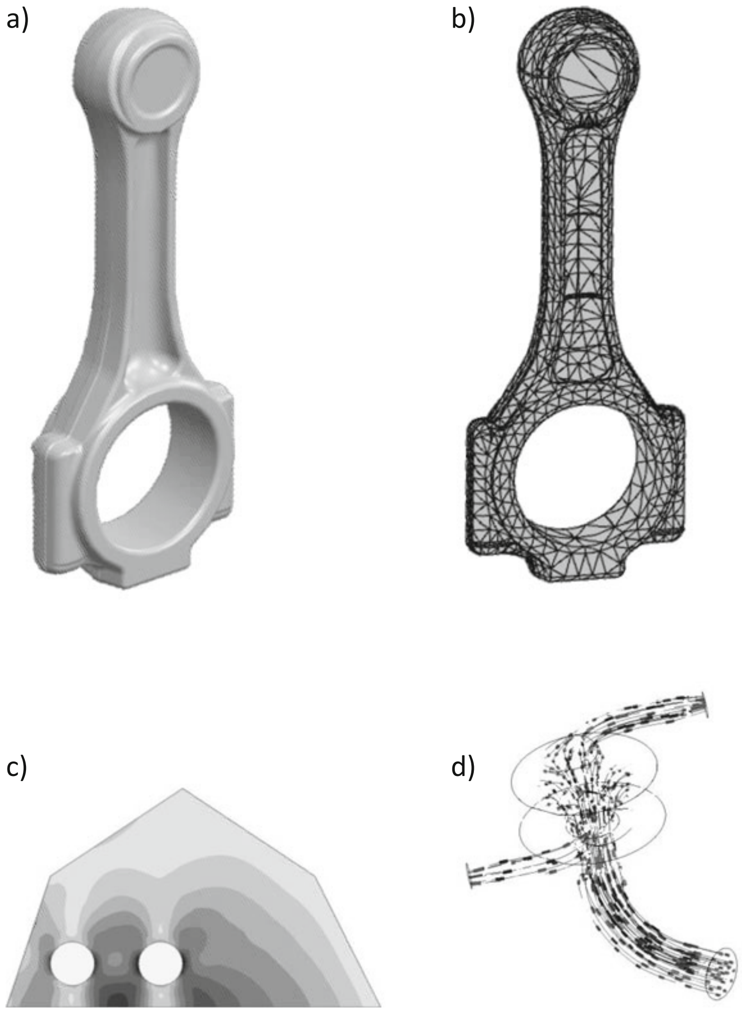

Fig. 1.2 Examples of simulation tools. (**a**) CAD-model. (**b**) FEM-mesh. (**c**) Stresses around tunnels in a mountain (BEM). (**d**) Flow through a nozzle pair (FVM)

of individual engineers could perform much of the computation, there was no longer a need for large central mainframes. More importantly, the FEM-meshes could be easily derived from the 3D-CAD-Models. Only with these advancements would FEM became a tool available to more diverse segments of industry as well.

The new, less expensive application of FEM and other simulation systems, such as BEM or the Finite Volume Method (FVM) for fluid mechanics problems, opened up possibilities to apply field-integrated optimization (Fig. 1.2). It was once acceptable to spend hours building a model. But it is far too expensive to spend many hours on the repeated process than to build and study variants of the initial design.