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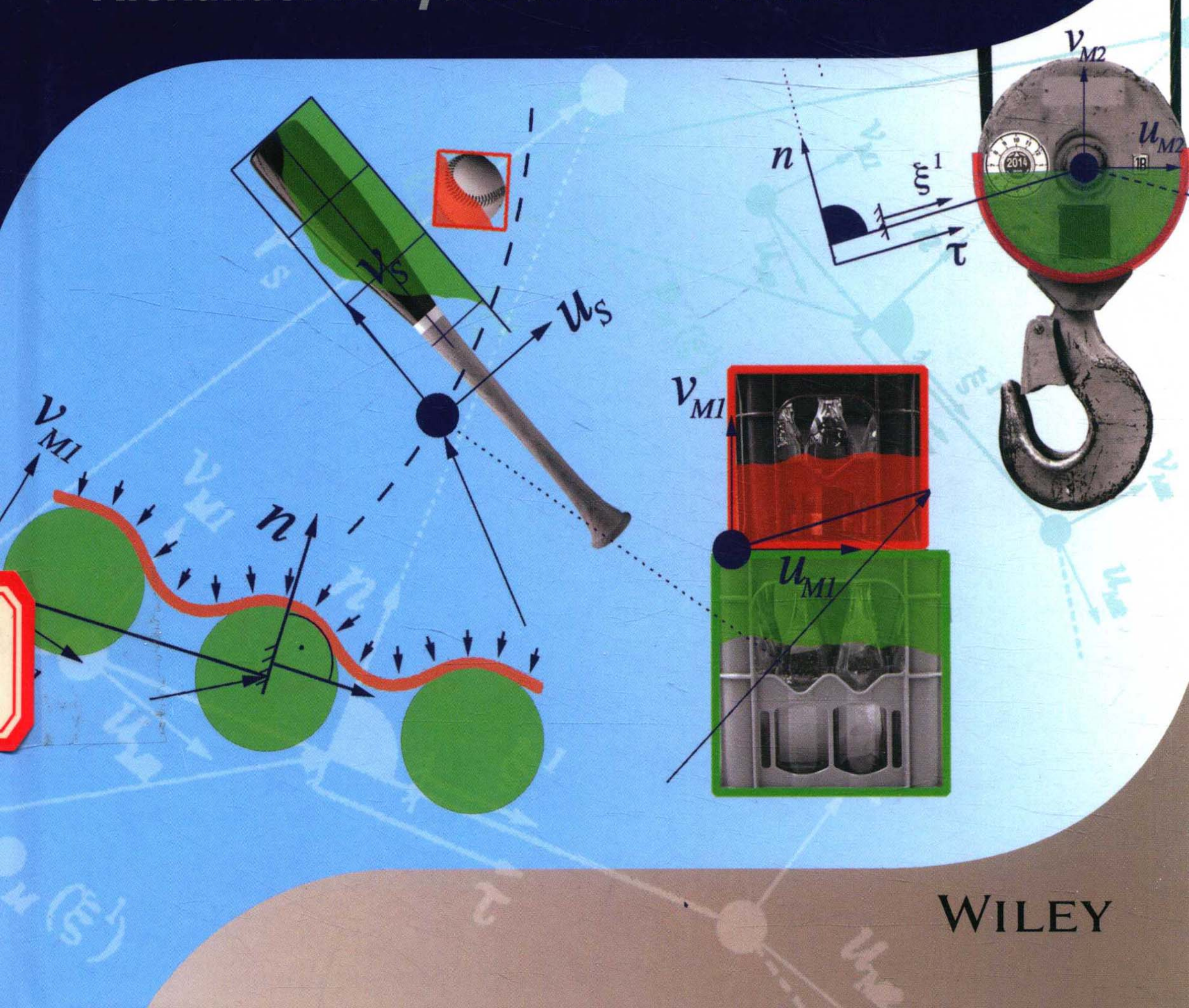
Introduction to Computational Contact Mechanics

A Geometrical Approach

Alexander Konyukhov and Ridvan Izi



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Series Preface

Since the publication of the seminal paper on contact mechanics by Heinrich Hertz in 1882, the field has grown into an important branch of mechanics, mainly due to the presence of a high number of applications in many branches of engineering. The advent of computational techniques to handle contact between deformable bodies has greatly enhanced the possibility of analyzing contact problems in detail, resulting, for instance, in an enhanced insight into wear problems. The numerical treatment of contact belongs to the hardest problems in computational engineering, and many publications and books have been written to date, marking progress in the field. An *Introduction to Computational Contact Mechanics: A Geometrical Approach* stands out in terms of the clear and geometric approach chosen by the authors. The book covers many aspects of computational contact mechanics and benefits from clear notation. It comes with detailed derivations and explanations, and an exhaustive number of programming and verification tasks, which will help the reader to master the subject.

Preface

Computational contact mechanics within the last decade has developed into a separate branch of computational mechanics dealing exclusively with the numerical modeling of contact problems. Several monographs on computational contact mechanics summarize the study of computational algorithms used in the computational contact mechanics. The most famous, and subject to several editions, are the monographs by Wriggers (2002) and Laursen (2002). Most of the topics are explained at a high research level, which requires a very good knowledge of both numerical mathematics and continuum mechanics. Therefore, this book was the idea of Professor Dr. Ing. Schweizerhof back in 2006, who proposed to me to introduce a course in computational contact mechanics in such a manner that the prerequisite knowledge should be minimized. The main goal was to explain many algorithms used in well-known Finite Element Software packages (ANSYS, ABAQUS, LS-DYNA) in a simple manner and learn their finite element implementation. The starting point of the course was a reduction of the original 3D finite element algorithms into the 2D case and an introductory part to differential geometry. As field of the research has developed, the exploitation of the geometrical methods, the so-called covariant approach, after years of research has lead to the joint research monograph together with Professor Dr. Ing. Schweizerhof in Konyukhov and Schweizerhof (2012) *Computational Contact Mechanics: Geometrically Exact Theory for Arbitrary Shaped Bodies*. At this point, we would like to mention other monographs that we recommend for reading in computational contact mechanics Kikuchi (1988), Sofonea (2012), Yastrebov (2013), in friction and tribology Popov (2010) and also, the famous book on analytical methods in contact mechanics by Johnson (1987).

Ridvan Izi joined the computational contact mechanics course in 2009 and started to give assistance from 2011 to the exercise programming part, and made a lot of effort to make the exercises "easy going" for the students. Thus, the joint work started, leading to the current structure of the exercises in Part II. We were trying to keep this structure independent as much as possible from the programming language, although the course has been given in FEAP (Finite Element Analysis Program) written in FORTRAN.

The current book is based on the course being taught over several years at the Karlsruhe Institute of Technology and proved to be an effective guide for graduate and PhD students studying computational contact mechanics. The geometrically exact theory for contact interaction is delivered in a simple attractive engineering manner available for undergraduate students starting from 1D geometry.

The book is subdivided into two parts:

- Part I contains the theoretical basis for the computational contact mechanics, including necessary material for lectures in computational contact mechanics.
- Part II includes the necessary material for the practical implementation of algorithms, including verification and numerical analysis of contact problems. Part II is consequently constructed following the theory considered in Part I.
- In addition, the original FORTRAN programs, including all numerical examples considered in Part II, are available from the supporting Wiley website at www.wiley.com/go/Konyukhov

The basis of the geometrically exact theory for contact interaction is to build the proper coordinate system to describe the contact interaction in all its geometrical detail. This results in the special structure of the computational mechanics course – study in applied differential geometry, kinematics of contact, formulation of a weak form and linearization in a special coordinate system in a covariant form. Afterward, most popular methods to enforce contact conditions – the penalty method, Lagrange multipliers, augmented Lagrange multipliers, Mortar method and the more seldomly used Nitsche method – are formulated consequently, first for 1D and then for 2D systems finally leading to examples in 3D. It then applies to finite element discretization. The structure of contact elements for these methods is studied in detail and all numerical algorithms are derived in a form ready for implementation. Thus, the structure of contact elements is carefully derived for various situations: Node-To-Node (NTN), Node-To-Segment (NTS) and Segment-To-Segment (STS) contact approaches. Special attention is given to the derivation of contact elements with rigid bodies of simple geometry such as the Segment-To-Analytical Segment (STAS) approach.

Part II of the book contains programming schemes for the following finite elements: surface-to-analytical (rigid) surface, NTN for several methods: penalty, Lagrange, Nitsche methods; node-to-segment for both non-frictional and frictional cases, with Mortar type segment-to-segment and 3D node-to-segment contact elements. Through examples, special attention is given to the implementation of normal following forces, which is derived a particular case of implementation for the frictionless contact algorithm.

All examples are given in a sequential manner with increasing complexity, which allows the reader to program these elements easily. Though the course has been designed for the FEAP user using FORTRAN, the structure of all examples is given in a programming-block manner, which allows the user to program all elements using any, convenient programming language or just mathematical software such as MATLAB.

The examples and corresponding tests are conceptualized in order to study many numerical phenomena appearing in computational contact mechanics, such as influence of the penalty parameters, selection of meshes and element type for the contact patch test for non-frictional and frictional cases.

The original implementation of the derived contact elements was carried out in one of the earliest versions of FEAP originating from Professor Robert Taylor, University of California, Berkley. The Finite Element Analysis Program (FEAP) appeared at the Institute of Mechanics of the Karlsruhe Institute of Technology due to the joint collaboration between Robert Taylor and Karl Schweizerhof who further developed the FEAP code into FEAP-MeKa with the famous solid-shell finite element. The code used in the current course is a simplified student version without any finite elements used for research and is used for educational purposes. During private communications, Professor Taylor confirmed that a free updated version is available and is still supported at http://www.ce.berkeley.edu/projects/feap/feappv/. I am particularly thankful for his kind agreement to link the programming given in the current course to the updated version of FEAP. Though all originally implemented subroutines for contact elements are shown within the old version of FEAP (or FEAP-MeKa) together with all necessary specifications (geometry, loads, boundary conditions, etc.) of tasks, the subroutines can be easily rearranged for the updated version of FEAP. The code, together with numerical examples, is essential in order to work with examples given in Part II. Any reader familiar with FEAP can straightforwardly adopt this code to his/her needs. The code is written in FORTRAN, but the straightforward programming structure, without using any math library, is intentionally preserved in order that any user can easily adopt the code to any other programming language. Moreover, we do really hope that the flowcharts, provided for each contact element can be used for programming of computational contact mechanics exercises using symbolic mathematical software such as MATLAB, MATHEMATICA, and so on.

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Acknowledgments

We are thankful to Professor Karl Schweizerhof for giving us the great opportunity to develop such a course for students.

We would like to thank Professor Robert Taylor for his kind agreement to link our course of computational contact mechanics to the current and updated version of FEAP, thus encouraging us to work with the current code. Professor Taylor confirmed that the free version is available and is still supported at http://www.ce.berkeley.edu/projects/feap/feappv/.

The group of excellent student assistants has been busy carefully testing all examples given in Part II in less than a year. We would particularly like to thank Christian Lorenz, Merita Haxhibeti, Isabelle Niesel and Oana Mrenes for careful testing of the contact mechanics examples and Marek Fassin for testing necessary structural finite elements. An additional thanks to Oana Mrenes for the many editing efforts made with contemporary LATEX packages.

Many thanks to Johann Bitzenbauer for the careful reading of the current manuscript version and his fruitful proposals that lead to improvement.

The book in its current version has been tested in a workshop for computational contact mechanics recently at the Bundeswehr Universität München – and we are thankful to Georgios Michaloudis for his careful reading and proposals.

The work on this book took us many weekends, sacrificing time spent with our families. At this last, but not least point, we would like to especially thank our families for their understanding and moral support during the work on this book.

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