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Mechanics of Solids and Fluids

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Mechanics of Solids and Fluids

To the Students Who Accept the Challenge of Science
and to My Children Robert and Eva C.

Preface

This book offers a unified presentation of the concepts and most of the practicable principles common to all branches of solid and fluid mechanics. Its design should be appealing to advanced undergraduate students in engineering science and should also enhance the insight of both graduate students and practitioners. A profound knowledge of applied mechanics as understood in this book may help to cultivate the versatility that the engineering community must possess in this modern world of high-technology.

This book is, in fact, a reviewed and extensively improved second edition, but it can also be regarded as the first edition in English, translated by the author himself from the original German version, "Technische Mechanik der festen und flüssigen Körper," published by Springer-Verlag, Wien, in 1985.

Although this book grew out of lecture notes for a three-semester course for advanced undergraduate students taught by the author and several colleagues during the past 20 years, it contains sufficient material for a subsequent two-semester graduate course. The only prerequisites are basic algebra and analysis as usually taught in the first year of an undergraduate engineering curriculum. Advanced mathematics as it is required in the progress of mechanics teaching may be taught in parallel classes, but also an introduction into the art of design should be offered at that stage. The book is divided into 13 chapters that are arranged in such a way as to preserve a natural sequence of thought and reflections. Within a single chapter, however, the presentation, in general, proceeds from the undergraduate to intermediate level and eventually to the graduate level.

The first three chapters are devoted to the basic components of the mechanical modeling of systems at rest or in motion. They are followed by a chapter on constitutive relations ranging from Hooke´s law and Newtonian fluids to that of visco-plastic materials. Vector and cartesian tensor notation is applied consequently, but one-dimensional relations of standard material testing are always given priority. Students familiar with the programming techniques of field variables will have no difficulty following this text.

Kinematics of material points and particle fields including both pathlines and streamlines, as well as the conservation of mass; statics, providing experience with forces and stresses including hydrostatic pressure fields; mechanical work, and force potentials, are the prerequisites that, in Chap. 5, allow early exposure to the powerful principle of virtual work. Since force is recognized to be flux in the potential field, even an extension to nonmechanical systems with other driving agents becomes evident.

In the lengthy Chap. 6, material on linearized elastostatics is assembled but selected to serve the needs of structural mechanics. Thermal effects in beams, plates, and shells are given special attention in relation to load stresses in order to prepare the student for design considerations of the high-temperature environment of modern structures. The elastic visco-elastic correspondence principle serves as the vehicle for applying elastic solutions in order to determine stationary creep and solve the associated lifetime problems. At this stage, the Laplace transformation enters like the previous considerations of Chap. 4 in the form of operational calculus. Straight and curved beams, simple frames, plates, and shells of revolution are considered; torsion and the Hertz theory of contact are given special attention.

While disks and rings in stationary rotation are already considered in elastostatics, the Euler-Cauchy equations of motion are the starting point of Chap. 7 and highlight the transition from the statics of a material point at rest to the dynamics of a moving point. The conservation of both momentum and angular momentum is formulated for moving bodies enclosed in a material volume, and for the flow through a control volume that is fixed in space, or for the case in which the control surface is in prescribed motion. Prerequisites are the Lagrangean and Eulerian kinematics of Chap. 1. The control volume concept is immediately applied to determine the guiding forces of stationary flow and to explain the thrust of rockets and jet engines. Euler's turbine equation is derived, and the drag and propelling forces in a parallel viscous main stream are determined. The vector of angular momentum is further defined for rotating rigid bodies, and the generally valid formula for taking the time derivative of a vector with respect to an intermediate (rotating) reference frame is quite naturally derived. Euler's equations of gyros are discussed as well. In connection with the material on rigid-body kinematics of Chap. 1, the important field of (nonlinear) multibody dynamics (eg of vehicles and satellites) is addressed. Sections on linear and nonlinear vibrations present not only useful integration techniques in both the time and frequency domain, but also illustrate pure dynamic phenomena, like resonance and phase shift. Blake's logarithmic diagram is introduced.

The coupled equations of motion of an unbranched chain of spring-mass systems are derived by means of Newton's law, and the modal properties of its natural vibrations are determined by means of the Holzer-Tolle procedure. Stodola's matrix iteration scheme is sketched in Exercise A 11.11. The practically important design of vibrational absorbers is considered in general in Chap. 7 and for torsional vibrations in Chap. 10.

Using the free-body diagram of a high beam element, the partial differential equations of a vibrating Timoshenko beam are derived. Plane body waves and the associated linear eigenvalue problems and the Rayleigh surface wave are included in this chapter to enhance the understanding, eg of ultrasonic techniques. They are applied in material testing and for medical diagnosis. Seismic waves, namely, the loadings in earthquake engineering, should be mentioned here, as well as the water hammer in hydraulic engineering. Some illustrations are given in Chap. 11 and 12.

A first integral of the equations of motion is useful for both solids and fluids. A first example, the planar pendulum, is already analyzed along these lines of general validity in Chap. 7. Thus, in Chap. 8 not only the work theorem of dynamics and its special form of conservation of mechanical energy is derived by proper integration over the material volume, but also integration performed along a given streamline, keeping the time constant, renders the generalized Bernoulli equation of fluid dynamics. The latter is specialized to the stationary flow of ideal fluid and recognized to be the law of conservation of the specific mechanical energy of a particle moving along the streamline and pathline. Interpretations of hydraulic measurements of stationary flow are given by means of that original Bernoulli equation. Generalizations to include the power supply of a stationary stream and, thus, the loss of pressure head of a guided ideal flow through a turbine or the pressure gain of a flow through a pump and the loss of energy head in a viscous stream are discussed in some detail. Relative streamlines with respect to a stationary rotating reference frame are considered, and a proper form of a Bernoulli-type equation is derived to further ease the application of fluid dynamics to rotating machines. The extension to the first law of thermodynamics (of material and control volumes) concludes that introductory chapter on energy conservation, and it is hoped that the gap between the mechanics course and a parallel course on thermodynamics is thereby somewhat narrowed. The Clausius-Duhem inequality is only mentioned. Fourier's law of heat conduction, however, as an outcome of an irreversible process is stated and applied in Chap. 6.

Chapter 9 on stability starts out with the derivation of the Dirichlet criterion in an energy norm by means of small perturbations applied to a conservative mechanical system at rest. Thus, the dynamic nature of instability is stressed from the very beginning. The conservation of mechanical energy of the perturbing motion and the assumption of minimal potential energy of the equilibrium configuration render the proper inequalities that bound the kinetic and potential energy in the nearfield of the equilibrium configuration. Bifurcation, snap-through, and imperfection sensitivity are discussed and well illustrated in the load factor deformation diagram. The Euler buckling of slender columns and the buckling of plates are generally discussed; further examples are given in Chap. 11. In addition, the method of small perturbations is applied to consider the stability of a principal motion.

The limits of stability of ductile structures are discussed and the ultimate loads of simple beams and frames determined. Safety analysis within structural mechanics like a cross-sectional and plastic system reserve follows quite naturally. Melan-Koiter's shake-down theorems are formulated and applied to a plastic thick-walled spherical pressure vessel under lifepressure loading. Consideration of the stability of an open-channel flow and of instability as a result of flutter round off this first overview based on phenomena, rather than mathematics.

The knowledge of dynamics of MDOF-systems is further expanded in Chap. 10, where the Lagrange equations of motion (of the second kind), the outcome of the more general D'Alembert's principle are presented. The latter is derived in quite the same fashion as the principle of virtual work in statics. Only dynamic systems under holonomic constraints are considered and a few applications to vibrational systems given. A spring-mounted foundation in coupled translational-rotational motion is treated in some detail to illustrate the dangerous beat phenomenon. Parametric excitation is shown to occur in a pendulum with a periodically moving support. Matrix structural dynamics is encountered when considering a simple beam with lumped masses.

The principle of virtual work as presented in Chap. 5 and 10 is the basis for the important approximation techniques and discretization procedures associated with the names of Rayleigh, Ritz, and Galerkin. Chapter 11 offers a rather complete account from a purely mechanical standpoint and also gives a short introduction to the finite-element method (FEM). Convergence in the mean square of the outcome of the Galerkin procedure is conserved if the equations of equilibrium or motion containing the forces are subject to approximations. A generalized form is discussed that makes application as convenient as the original Ritz approximation. Any practical application of some complexity, however, requires further consultation of the specialized literature and a gradual buildup of experience. Priority is given in this context to examples in which additional mechanical insight can be gained: For example, the buckling of a slender rod under the influence of a Winkler foundation exhibits mode jumping, and flexural vibrations under moving load excitation illustrate another type of effective structural bending stiffness in addition to critical speeds, to name just two illustrations of considerable engineering importance. The reduction in time of a nonlinear ordinary differential equation of motion is shown by the Ritz-Galerkin approximation of the Duffing oscillator, by harmonic balance, and by means of the Krylow-Bogoljubow approximation.

In Chap. 12, which deals with impact dynamics, most of the material is related to the simplest possible modeling. The exchange of momentum is assumed to be a sudden process, ie the velocity fields of the colliding masses suffer a jumplike redistribution. Only the two extreme physical cases of idealized elastic impact with conservation of total mechanical energy and the inelastic impact of extreme dissipation are elaborated within that context. To illustrate and justify some of these assumptions, a thin elastic rod of finite length is considered, taking into account the back and forth running waves following a short and hard impact. Thereby, the sound speed of rods is introduced, in addition to the wave speeds derived in Chap. 7. Similarly, water hammer in a suddenly shut down lifeline is reconsidered, examining the compressibility of the fluid and the elasticity of the walls of a cylindrical pipe. The crude approximation derived in Chap. 7 for a draining pipe may be seen as limited to the quasistatic closure of the gate. The sound speed in that case depends on the stiffness of springs in a series connection.

The last, Chap. 13, completes to some extent the discussion of fluid dynamics. More important, the lift exerted on a body in an ideal flow is related to circulation, in addition to being just the result of the surface tractions. The Navier-Stokes equations of viscous flow and their nondimensional form are explored, providing further motivation for the introduction of the Reynolds´ and Froude´s numbers. Similarity solutions with respect to the drag coefficient, the viscous flow through a pipe, and the boundary layer of a flow along a semiinfinite plate are the few applications possible due to the limited length of this book. Since the singular nature of perturbation of the ideal flow through viscosity becomes evident in many cases to be limited to the boundary layer, the importance of the outer flow that may be assumed the ideal is recognized. Therefore, potential flows are discussed and some fields of streamlines derived. The singularity method is a major tool of analysis and its basic idea is sketched; the formulas of Blasius are then derived. The force exerted on a body by a von Karman street of vortices is calculated and the Strouhal number introduced. The boundary value problem of kinematic waves excited in a fluid strip of finite depth by a moving rigid and linear elastic wall is solved to illustrate one of the important interaction problems and to show mode coupling. The Mach number and supersonic flow of gas dynamics are discussed by considering the isentropic outflow of gas through a nozzle from a pressure vessel.

Each chapter not only contains more or less concise derivations, but also exclusively shows practical applications. A book on mechanics cannot be read like a novel. The reader is expected to work out examples with paper and pencil or a personal computer and to have a good command of a suitable programming language, eg FORTRAN. Exercises are presented in an appendix to each chapter. Some test general problem-solving skills, some contain new material. However, hints when possibly needed are always given, together with complete solutions. Other collections of examples should be consulted.

This book was influenced by the standards of teaching mechanics at Northwestern University, Stanford University, and Cornell University, schools the author visited several times and in the order cited. It is a textbook designed for classroom teaching or self-study, not a treatise reporting new scientific results. The author is obviously indebted to many investigators over a period of more than two centuries, as well as earlier books on mechanics. Extensive bibliographies may be found in the *Encyclopedia of Physics,* published by Springer-Verlag, Berlin, and various handbooks of engineering mechanics and fluid mechanics. Also, the regular volumes of *Applied Mechanics Reviews* , published by ASME, New York, should be consulted. The classic textbooks written by the late Professor Timoshenko must be mentioned here. The first edition of this book published in German by Springer-Verlag Wien, had its roots in H. Parkus's *Mechanics of Solids* (in German). Most of the figures of the first edition have been used to illustrate this book. The author is indebted to several colleagues at the Technical University of Vienna for promoting this book in their classes and to a number of former graduate students, including Dr. P. Fotiu (UC-San Diego), Dr. N. Hampl (now with Getzner Chemie), Dr. R. Hasenzagl (now with Control Data), Dr. H. Hasslinger (now with AMAG), Dr. H. Hayek, Dr. R. Heuer, Dr. F. Höllinger (now with the Danube-Power), Dr. H. Irschik (Professor of Mechanics, U-Linz), Dr. F. Rammerstorfer (Professor of Light-Weight Structures and Aircraft Design), Dr. W. Scheidl (chief engineer of Elin). Their encouragement and helpful criticism and the numerous other contributions by students of civil and mechanical engineering made this book possible.

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Please forward any suggestions that might lead to an improvement of the text to the author or Springer-Verlag.

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