Preface

Mechanics as a fundamental science in Physics and in Engineering deals with interactions of forces resulting in motion and deformation of material bodies. Similar to other sciences Mechanics serves in the world of Physics and in that of Engineering in a different way, in spite of many and increasing interdependencies. Machines and mechanisms are for physicists tools for cognition and research, for engineers they are the objectives of research, according to a famous statement of the Frankfurt physicist and biologist Friedrich Dessauer. Physicists apply machines to support their questions to Nature with the goal of new insights into our physical world. Engineers apply physical knowledge to support the realization process of their ideas and their intuition. Physics is an analytical Science searching for answers to questions concerning the world around us. Engineering is a synthetic Science, where the physical and mathematical fundamentals play the role of a kind of reinsurance with respect to a really functioning and efficiently operating machine. Engineering is also an iterative Science resulting in typical long-time evolutions of their products, but also in terms of the relatively short-time developments of improving an existing product or in developing a new one. Every physical or mathematical Science has to face these properties by developing on their side new methods, new practice-proved algorithms up to new fundamentals adaptable to new technological developments. This is as a matter of fact also true for the field of Mechanics.

In the 20th century a couple of significant ideas pushed forward the classical field of dynamics, both, with respect to physics and with respect to engineering. In the first half of the 20th century we had, seen from the standpoint of physics, three theories of dynamics, Newtonian dynamics, relativistic dynamics and quantum dynamics [257]. We had four decisive impacts the last hundred years, two with respect to the basis of dynamics and two with respect to applications.

Starting with the at his time revolutionary idea of geometric dynamics by Henri Poincaré [214] some new features of dynamics came up, which should change dynamical arguing considerably, namely the aspects of bifurcations and chaos characterizing the broad field of "Nonlinear Dynamics" [261]. Viewing it from a broader physical basis, Prigogine [218] stated that "we are led from a world of *being* to a world of *becoming*", which indeed fits perfectly well into the concept of engineering. Research in this field comes out with a completely new way of looking at dynamics in form of a topological evolution of mechanical systems with time. Research is going on, there are still open questions related to large systems, to optimization and control. Impact on practical problems is coming up more and more.

The second basic contribution to dynamics consists in creating "non-smooth mechanics", first addressed to by Moreau in Montpellier [160] and by Panagiotopoulos in Thessaloniki [176]. The new theories of non-smooth mechanics added to the idea of bilateral constraints the new idea of unilateral constraints as they appear for example in contacts. The fundamental non-smooth principles are for my opinion comparable to the idea of the principle of d'Alembert-Lagrange and on an equal scientific level. They open large new fields, theoretically and practically. In the meantime progress in that field especially with respect to the classical and non-smooth principles of mechanics clearly indicate, that classical mechanics is embedded in the theories of non-smooth mechanics, it is indeed a subset of it.

Two more application-oriented concepts came up in parallel with the technical development of computers and of space technologies. During the fifties and sixties of the last century the idea of finite element discretization was pushed forward opening new applications especially for new aerospace projects, moving more and more the necessary investigations from experimental fields to computer simulations. Today FEM-codes are commercially available and applicable in all fields of modern technologies. Nevertheless research is going on. The second idea concerns multibody systems, a picture-book model for the application of the constraint ideas well-known since Bernoulli [18]. Therefore quite a number of impressive ideas were published in the 18th and 19th century [43], but a final impact to develop formulations as available today was given by space applications of the fifties and sixties [110]. Also in this field research is going on.

We are living in a world of computers and computing techniques, and we profit from it. Simulations with large and in the meantime very comfortable computer codes allow to establish a virtual world, which, applied in an intelligent way, might give detailed and very helpful insights into the concepts of new products. The development times for new cars or machines have been reduced considerably with the help of computer application. On the other hand we have to be careful. The engineering process requires perfect insight into the physics of a system, thus also into the mechanics of a machine. Engineering thought cannot be replaced by a computer, neither in design, material selection and cost analysis nor in the physical fundamentals like mechanics and others. Every real progress in technology is always accompanied by considerable thought of large depth. Mechanics and mathematics are perfect training areas for such thinking.

In the following we shall consider fundamentals and applications of dynamics, mainly with respect to large dynamical systems typical for modern industry and its products. The bases are models. Models are pictures of thought or constructs of ideas. Using models includes several aspects. Firstly, there are the simple ones, which nevertheless represent the main features of a problem, for example of a vibration problem, in such a good way, that they can be used to give some analytical insight into that problem with regard to dynamics but also with regard to parameter influences. Establishing such models is an art for a very few number of experts. It requires a perfect knowledge of the specific problem under consideration, and it affords intuition and intelligence to reduce such a system to a few parameters. But we often can learn from such models in a couple of days much more than by long-lasting computer simulations.

Secondly, we may establish models by considering as many details as possible. Such models are large and costly regarding computing times. And even in this case we have to investigate very carefully all physical effects for doing the correct neglects without endangering realistic results. Done in a skillful way such models are the basis for physical understanding and for improving design concepts. These two types of models aim at generating some results, which are as realistically as possible related to our real world problem.

Thirdly, if we leave that requirement, we may find models with similar features as our real world case, but only in a more or less qualitative sense. This might help sometimes, but usually it is too far away from practice. Anyway, establishing models represents more an intuitive art than a science. This is mostly underestimated, because only good models in a mechanical sense, at this stage not in a mathematical sense, give access to good solution algorithms and finally to good results. Models should be as simple as possible and so complex as necessary, not more and not less.

As a rule we understand the word model as a theoretical construct. But model and modeling applies in the same way to experimental set-ups. Lack of thought very often identifies experiments with the dogmatic truth of practice, which is only sometimes true. To design and to establish good experiments really related to the practical system under consideration is a difficult task. And it is also a difficult task to find the correct interpretations of measured data. Let us take a measured spectrum of an airborne gas turbine system, and let us find out, if there are hidden self-exited vibrations or not. And if we find them, how does the mechanism of these self-excitations look like? We could continue such examples of open questions. Therefore, comparing theory and measurement requires very much care on both sides, on the side of theory and that of experiments.

The development of computers during the last forty years has created a certain dualism within all Sciences, namely the "Science" itself usually addressed to as being purely theoretical and far away from any computer application, and the "Computational Sciences", which have a clear focus in computer algorithms and applications. In Mechanics we have the same situation, which half a century after the first computers is not only obsolete, but also a bit out-dated and old-fashioned. Computers are used to solve complicated and large mathematical problems from Finite Elements (FEM) over Multibody Systems (MBS) to Computer Aided Design Systems (CAD), to name only a few, or to establish virtual worlds on the basis of topological structures or the like. In all cases we need a lot of fundamentals, and in all cases the colleagues involved in this kind of research are elaborating also some theoretical basis. On the other hand the "pure scientists" apply computers, be it to test their theoretical findings, be it to develop symbolic structures with the help of computers. Therefore the time is overdue, that these dualisms disappear.

The concept of the book is mainly determined by the experiences of the author. Sixteen years aerospace industry with its forerunner role in all technologies, but also in many fundamentals, twenty years academia in the area of mechanics, especially in the areas of dynamics and control, fundamental research on bilaterally and unilaterally constrained systems, on robotics and walking machines and many applications with regard to practical industrial problems have taught me, that for an engineer the combination of physical, mathematical and of practical, empirical knowledge is an indispensable prerequisite for successful professional work. We say, that a good theory is very practical, but we also have to state, that good practice might induce good new theories never known before. Both is important for a good engineer. The book tries to follow these ideas presenting in the first part the theoretical foundation of dynamics and in the second part a collection of industrial examples. Both theory and practice were topics of more than eighty dissertations being carried through during my activities as Professor and head of an Institute at the Technical University of München.

In spite of the fact that many research activities of the last two, three decades include also control design and development, the book will not consider this topic from the theoretical standpoint of view but more within the applications. Doing research in dynamics, especially in dynamical systems, implies also control in the one or other form, because control systems are also dynamical systems with the additional possibility of own decision capabilities. We shall focus on general dynamics, on multibody system dynamics including rigid and elastic components and on the consequences of bilateral and unilateral constraints. Unilateral contacts were and still are a matter of significant research at my former Institute.

Finally I have to thank many people and many Institutions. First of all, I have to thank my doctoral students of the last twenty years, who elaborated in dozens of theses my and their ideas on dynamics providing me with an excellent basis for this book. Many of them can be detected in the literature survey. I have to thank Prof. Christoph Glocker of the ETH Zurich for many fruitful discussions, mainly on non-smooth problems. And I am indebted especially to Dr.-Ing. Martin Foerg, who did some excellent proof-reading and has been for me during his time as doctoral student of my successor a continual contact for many discussions about fundamental problems of dynamics. The same is

true for Dr.-Ing. Thomas Geier, who worked on very challenging applications like the pushbelt CVT. I could not have written this book in LaTex without many good advices and ideas concerning LaTex-questions from another doctoral student of my successor, namely Dipl.-Ing. Sebastian Lohmeier, who for his thesis is realizing the new walking machine LOLA, but who is also a real expert in LaTex.

Last but not least I do thank the Technical University of Munich, its Department of Mechanical Engineering and especially my successor, Prof. Heinz Ulbrich, for the opportunity to continue my work at the TU-Munich also after my retirement. A really big help for me were the co-workers of the Springer publishing house in Heidelberg, Dr. Thomas Ditzinger and Dr. Dieter Merkle from the organizational and contract side and Frank Holzwarth for all questions concerning the Springer stylefile. Many thanks to all.

A book cannot be written without any errors. Therefore I would like to motivate the readers of this monograph to give me a message of possible errors, he or she has detected. This concerns also any kind of concept or style aspects. I shall be very grateful for indications of that kind.

Garching, December 2007 *Friedrich Pfeiffer*

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