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Courses and Lectures

Friedrich Pfeiffer
Hartmut Bremer *Editors*

The Art of Modeling Mechanical Systems

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for Mechanical Sciences

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The Art of Modeling Mechanical Systems

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Preface

Engineering and Physics cannot be thought of without models; models, which represent the real world to the best of our knowledge. And before we start with any mathematical description, with any mathematical model, we have to establish something like a phenomenological picture, a symbolic map of the real-world structures with elements like masses, springs, dampers, fluid system, thermodynamic elements and so forth and, not to forget, with elements of interconnections frequently more complex than the elements themselves.

This very first step of physical or mechanical modeling is mostly underestimated, but it decides very substantially about the success of all following activities like mathematical modeling, numerical algorithms, and finally computer codes. Therefore, it is worth looking at that more systematically, in spite of the fact that there does not exist any systematic approach to these problems. It is still more an art than a science.

Good modeling requires a deep insight into the performance of the real-world artifact, may it be a machine, an airplane, or human walking. We must understand how it works, in terms of operations, functions, dynamics, kinematics, stability and deformation, noise and wear, and even costs. But this is only one important precondition. Other aspects are the goals and requirements connected with such models.

First, there are the simple models, 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.

Second, 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.

Third, 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 includes very strong phenomenological issues. 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 setups. 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. Therefore, comparing theory and measurement requires very much care on both sides, on the side of theory and that of experiments.

From all this we know, that modeling mechanical, and generally physical systems, requires insight and intuition, which usually is connected with long and broad professional experience. The course concerned with such a topic aims at presenting some rules for mechanical models in a more general systematic way always in combination with small and large examples able to illustrate the most important features of modeling. It will be not a course presenting mathematical solution algorithms, but discussing more advantages and disadvantages of potentially well-suited mathematical branches. It is a course with a strong focus on the art of modeling.

The following lectures have been given:

- Hartmut Bremer, Fascination of Making Models
- Friedrich Pfeiffer, Model Objectives and Realization
- Michel Raous, The Art of Modeling in Contact Mechanics
- Ahmed Shabana, Flexible Multibody System Dynamics
- Steven Shaw, Modeling for Nonlinear Behavior in Dynamics Systems
- Peter Wriggers, The Art of Modeling in Computational Mechanics

These lectures cover aspects of dynamics and also, to a certain extent, of continuum mechanics. They demonstrate, that the modeling problems have very much in common with respect to various fields, but of course with differences from the structural point of view. In the following these lectures will be presented in text-form.

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Contents

Modeling Objectives and Realization

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Abstract Engineering and Physics cannot be thought of without models; models, which represent the real world to the best of our knowledge. And, before starting with any mathematical description, we must establish something like a phenomenological picture, a symbolic map of the real world's structures with elements like masses, springs, dampers, fluid system, thermodynamic elements and so forth and, most important, with elements of interconnections.

This first step of mechanical modeling is mostly underestimated, but it decides very substantially about the success of all following activities like mathematical modeling, numerical algorithms and finally computer codes. Therefore, it is worth looking at that more systematically, in spite of the fact that there do not exist systematic approaches to these problems. Establishing models includes very strong phenomenological issues. Models should be as simple as possible and so complex as necessary, not more and not less. And all this is still more an art than a science.

1 Preface

Good modeling requires a deep insight into the performance of the real world's objects, may it be a machine, a building, an airplane or human walking. We must understand how it works, in terms of operations, functions, dynamics, kinematics, stability and deformation, noise and wear under given loading conditions. But this is only one important precondition. Other aspects are the objectives and requirements of models.

Firstly, very simplified models might nevertheless represent the main features of a problem in such a way, that they provide some physical insight especially with regard to parameter influences. Secondly, we may establish models by considering as many details as possible. Such models are large, costly and sometimes leading to cloudy results. But done in a skillful way such models are also the basis for physical understanding and for improving design. Thirdly, we may find models

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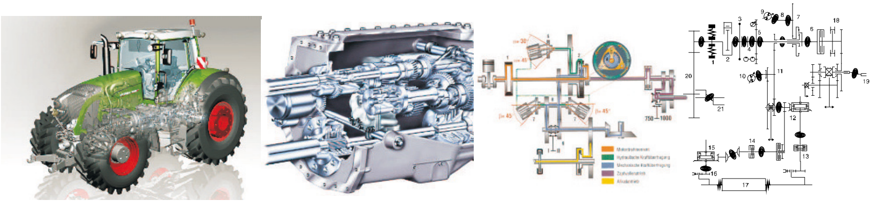

Figure 1: *The process of modeling shown by a tractor: the starting position for this example has been more or less perfect; hardware was existing, drawings and explosion charts were available, also a large body of experience and know-how by the design and test engineers; objectives were strength of certain components of the hydrostatic system during mulching and ploughing and vibration problems; models were comprehensive and complex; after successful verification with the company's measurements problems could be solved by parameter variations and corresponding design modifications.*

with similar features as our real world case, but only in a more qualitative sense. This might help sometimes to understand the physical background of a problem.

From all this we know, that modeling mechanical systems requires insight and intuition. The course concerned with such a topic aims at presenting some rules for mechanical models in a more general systematic way always in combination with small and large examples, many from industry, able to illustrate the most important features of modeling. It will be not a course presenting mathematical solution algorithms, but discussing the best and most efficient way to a good solution. The course has a strong focus on the art of modeling.

2 Mechanical Modeling

With respect to Technical Mechanics the aspect of *modeling* becomes one of the most important issues of mapping real world problems. Technical Mechanics is an engineering science, which considers motion or deformations of technical systems. They generate loads on machines, mechanisms and structures, which must be known for the design of such items. *Mechanical modeling* includes the replacement of a real machine, of real machine components or of real structures by certain basic elements. Considering mechanics this concerns for example masses, springs, dampers, frictional elements or finite elements with their shape functions which according to the topology of a structure must be interconnected in a physically correct way, usually leading to certain types of constraints. This process requires a deep insight into the operational problems of a machine and a sound knowledge of practice on the one and of mechanical theories on the other side.

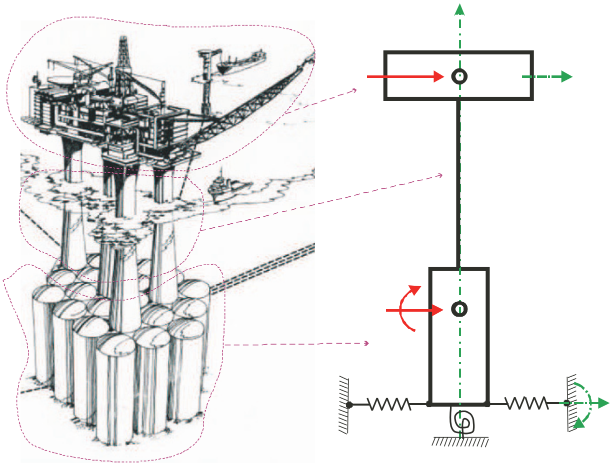

Figure 2: *A convincing example of "simple" modeling, but parameter estimates from a large FE-model: capsizing of an oil platform in the seventies in spite of large efforts during the design phase; for finding the reason with respect to this catastrophe Duncan [7] developed a simple model of the platform with 2-3 degrees of freedom and 3 different soil models for the sea ground; an additional FE-model has been used for finding the global parameters for the simple model; simple model results were convincing and explained the capsizing by some resonance behavior with the north sea wave spectrum, occurring very seldom.*

The quality of modeling decides on time and costs during a product development process, at least to a certain amount. Good models not only lead to quicker solutions, but also to better transparency of the problem under consideration and with it to accelerated achievements for a technical problem.

What is a *good model*, or better, what is a *good mechanical model*? A mechanical model will be a good one, if the mathematical model based on it gives us informations close to reality or for many cases close to a restricted reality, which might be of special interest to us. We have to anticipate, that reality is known, that it might be measurable or at least that it might be precisely describable. Therefore a good model should help us to come to a deeper understanding of the technical problems involved and of the design ideas behind them. To produce only numbers and charts will be not enough, we want to produce insight. Performing models has to keep that in mind.

How can we achieve a mechanical model? Usually we can assume, that every machine, machine component or structure offers some important operational functions, which are easy to describe and to model. With regard to our mechanical

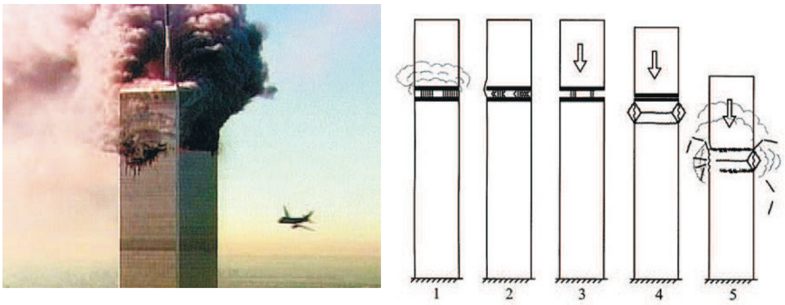

Figure 3: *An intelligent model for understanding the basic principles of a complete destruction: "The 110-story towers of the World Trade Center were designed to withstand as a whole the forces caused by a horizontal impact of a large commercial aircraft. So why did a total collapse occur? The cause was the dynamic consequence of the prolonged heating of the steel columns to very high temperature. The heating lowered the yield strength and caused viscoplastic (creep) buckling of the columns of the framed tube along the perimeter of the tower and of the columns in the building core." (from Bazant [2])*

systems these are for example some idealized motion sequences or vibrations, some effects from kinematics and kinetics. We start with that. Looking a bit deeper into such a structure, we might realize, that machines cannot be built in an ideal way, that we are confronted with disturbances, with "dirty effects", which in many cases cannot be modeled straightforwardly and the mechanics of which are often not understood really. Exactly at that point the typical work of an engineer starts to go on, which as a matter of fact possesses more an intuitive-empirical character than a scientific one, for example the question, what can be neglected. A good mechanical model is always a minimalistic model, too, not smaller than necessary, but also not larger than adequate to the problem involved. Finding intuitively neglects we may consider the geometric and kinematic situation, the order of magnitude of forces and torques or of work done and energy. Establishing a good model always needs an iteration process, which leads us with every step to a better solution. In his famous lecture on "Clouds and Clocks" from 1965 Karl Popper [31] tells us, that iterations are not only characteristic features of every intellectual work, but that they lead also from step to step to a deeper insight of the problem and to new questions finally achieving a really innovative solution, which at the beginning of such a process could not be perceived:

- mechanical modeling (theoretically and/or experimentally),
- examination with respect to plausibility, comparisons with reality,
- adaptation and improvements of models.

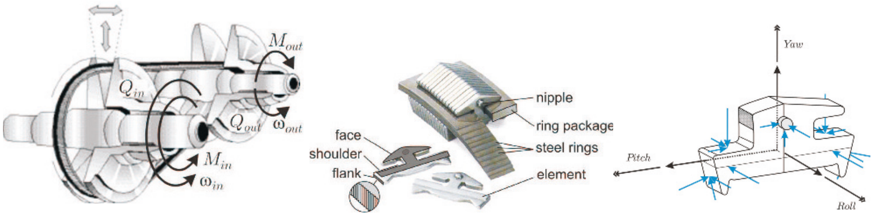

Figure 4: *A challenge of modeling, starting it even an efficient theory was missing: "Power transmission in automotive systems is classically carried out by gear trains, which transmit power by form-closure. In recent times an increasing number of continuous variable transmissions (CVT) are applied. They transmit power by friction, and at the time being they compete more and more with automated gears or with hand-shifted gears. The advantage of gear trains with gear wheels consists in a better component efficiency due to power transmission by form closure, the disadvantage in an only stepwise approximation of the drag-velocity hyperbola. This disadvantage is significantly reduced step by step by introducing automatic gear boxes with up to eight gear stages. The advantage of a CVT configuration consists in a perfect adaptation to the drag-velocity hyperbola, the disadvantage in a lower efficiency due to power transmission by friction and in a somehow limited torque transmission. An additional advantage of the CVT's is the possibility of very smoothly changing the transmission ratio without any danger of generating jerk. These features had to be evaluated by very detailed models, from belt approximations to every small component." (from Pfeiffer [24])*

Before doing this we have to define as precisely as possible, what should it be used for, what should be the outcome of our model, where should it be applied. With respect to these considerations we should regard the following aspects and problems:

- Motion (time response, frequency response): motion, motion patterns, frequency, damping, stability, amplitude and phase response functions.
- Control: If the system will be controlled, questions of observability, controllability, control quality, control stability and control optimization have to be answered.
- Perturbation: perturbation of the system, sensitivity of parameters, deterministic and stochastic perturbation.
- Optimization: Optimization of the dynamic system as a whole (process + controller) with respect to certain performance criteria, design strategies for the optimization of parameters and structures regarding sensitivities or other criteria.

The necessary methods involve a wide range of mathematics, system and control theory. They have multidisciplinary character.

3 Mathematical Modeling

Establishing a mechanical model we additionally have to watch some important aspects concerning mathematical and numerical modeling , that means the whole sequence of steps to a final solution of our mechanical model ideas:

- *discretization*: Can we compose our model only by rigid body elements or even by point masses or do we have to use also elements with a continuum-mechanical character? How shall we model such non-rigid bodies?
- The character of expected motion: Does some basic motion exist or do we have a type of *reference motion*? Is there some state of rest? Is it possible to describe the motion as one with a (usually nonlinear) reference motion and small deviations from it? Can we linearize, completely or in parts?
- *coordinates*: How many degrees of freedom includes our model? Can we find a set of coordinates, which corresponds directly to these degrees of freedom? If not, what sets of coordinates offer a formulation of constraints in a most simple way?
- *numeric*: What solution methods fit best to our problem, analytically (if any) or numerically? Can we put the mathematical formulation in a form, which corresponds in an optimal way to our solution possibilities? Is it possible to discover within our mathematical model and formulation already some qualitative or even quantitative results?

A perfect mechanical model, even a complicated one, will always be the simplest one possible, according to the well-known statement, that technology will be perfect if you cannot let out anything more. Especially for very complex systems we recommend to always start with a drastically simplified model for a better overview of the problems involved, if it is feasible. Then, in a second step, establishing a large model will be easier. In some cases it might be reasonable to go the other way round, namely to start with a large model and after some insights to break it down into smaller models. This depends on the particular problem, but as always also on the efforts which can be spent for a solution. Dresig [6] calls the first way inductive modeling and the second way deductive modeling. Anyway, a good comprehension of the problems will always come out with a better and faster development process.

Whatever method we use in mechanics, we always come out with a set of nonlinear differential equations of motion of first or second order, which are linear with respect to the accelerations but nonlinear with respect to velocities, positions and orientations. Very frequently we have to consider additional constraints and connections, which in many cases lead to differential-algebraic equations, the solution of which are nowadays also standard. All these equations represent the *mathematical model* of our problem and are an intermediate activity of our sequence (real world problem - mechanical modeling - mathematical modeling - numerical modeling - simulation). It should be kept in mind, that mathematics can give only results and information on a basis, which we have defined beforehand for example as assumptions and constraints of the mechanical model. Therefore, establishing the mechanical model requires extreme care, empirical knowledge and instinctive feeling combined with a good understanding of the mechanical problems, at least from a qualitative point of view. With respect to this step large expenditure can be generated but also omitted, if done intelligently.

The degrees of freedom (DOF) as expressed by minimal coordinates determine the size of the mathematical, of course before also of the mechanical model. Additional simplifications might be feasible by linearization, by using invariants of motion like energy integrals of conservative systems or by modifying the equations of motion, for example by transforming the differential equations. Anyway, we should try to find a set of minimal coordinates and if this is not possible, we have to add the relevant constraints or the relevant connections with force laws, but again trying to find a minimalistic formulation.

One could say, that this represents an old-fashioned procedure in the face of modern commercial computer codes, but it does not for two reasons: Firstly, technological progress is not possible without understanding the underlying problems, and the process described above helps significantly to increase our understanding. Secondly, also for computer codes the users have to establish a mechanical model, and it is advisable that this model will be carefully established on the basis of the same thoughts as discussed above. The quality of the results depend on such considerations. Commercial codes usually do not use a minimal formulation but a structure, which leads to fast and efficient numerical algorithms [41]. But interpretation of results depends as a matter of fact on the thorough understanding of the mechanical model and of the real world situation.

What we have mentioned does not depend on the choice of the mechanical laws we have applied, Newton-Euler, Lagrange, Hamilton, whatsoever. But on the other side, the choice of the mechanical foundation for the derivation of the equations of motion considerably influences the expenditure in establishing these equations. This has to be regarded very carefully. We shall discuss it in the following.

With respect to all possibilities for the derivation of the equations of motion we must perform kinematic groundwork, by the way one of the most frequent sources for errors and mistakes. The first step will choose coordinate systems, not to be underestimated, because a good choice helps to reduce effort, a bad choice produces effort. The second step must determine positions, orientations, velocities and accelerations, on the basis of these coordinate systems. In a third step we try to find minimal coordinates, and, if necessary, we establish the constraints. Velocities and