Dynamical Contact Problems with Friction

Walter Sextro

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MODELS, METHODS, EXPERIMENTS AND APPLICATIONS

With 133 Figures

Springer

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Originally published as volume 3 of the series Lecture Notes in Applied Mechanics, Springer-Verlag Berlin Heidelberg 2002.
Library of Congress Control Number: 2006940067

ISBN-10 3-540-69535-4 Springer Berlin Heidelberg New York
ISBN-13 978-3-540-69535-6 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media.

springer.com

Typesetting by the author and SPi
Cover design: Erich Kirchner, Heidelberg

Printed on acid-free paper SPIN 11405887 89/3100/SPi 5 4 3 2 1 0

Preface

Friction contacts are used to transmit forces or to dissipate energy. A better understanding of friction phenomena can result in improvements like the reduction of noise and maintenance costs, increased life time of machines and improved energy efficiency. There exists a rich literature on friction. Depending on the features of the friction contact, different contact models are applied and dependent on the contact model, different solution methods are preferred. The aim of this book is to describe an efficient procedure to model dynamical contact problems with friction. This procedure is applied to different practical problems and verified by experiments.

The dynamics of the elastic bodies in contact are described by a reduced order model through the so called modal description, to speed up calculations. This description is presented in Chap. 2. In Chap. 3 the generalized contact model is developed, which includes the main physical effects like contact elasticity, roughness, friction characteristics etc.. The contact planes are discretized and a point contact model is applied to each area element. The thermomechanics of the contact is investigated, as well as the calculation of wear. The application of the combined procedure of the point contact model and the modal description of the elastic components are illustrated by three different examples. An impact and friction oscillator, see Chap. 4, is investigated in the time domain, while the friction damping of elastic structures with expanded friction contacts is analyzed within the frequency domain, see Chap. 5. The stationary rolling contact is presumed to calculate the wear of wheel-rail-systems, see Chap. 6.

This work arose during my research at the Institute of Mechanics of the University of Hannover in Germany. Part of the work was supported by the "Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV, Frankfurt)" and was sponsored by the "Bundesministerium für Wirtschaft" through the "Arbeitsgemeinschaft industrieller Forschungsvereinigungen e.V. (AiF, Köln), (AiF Nr. 10684)", a federal collaboration of the turbomachinery-industry and the "Deutsche Forschungsgemeinschaft (Projekt Nr. SE 895/3-1)".

This book is based on the script that leads to my "Habilitation" in *Mechanics*. The "Habilitation" marks the end of the education as lecturer. In this context I would like to thank Prof. Dr.-Ing. habil. K. Popp, Prof. Dr.-Ing. habil. P. Wriggers and Prof. Dr.-Ing. habil. G.-P. Ostermeyer for carefully reading the script and for their support.

Furthermore, I would like to thank all of my colleagues at the Institute of Mechanics for the open discussion of any problems and the successful cooperation. I would especially like to emphasize Prof. Dr.-Ing. habil. K. Popp. During my time at the institute, he always supported me and therefore most of my thanks belong to him.

Hannover, 2002 Walter Sextro

Preface to the Second Edition

Since the last edition of this book the knowledge about friction has increased. Therefore several new results have been added like the wear calculation of a wheel-rail system as well as the efficient calculation of multi-coupled bladed disc assemblies with friction contacts.

This book can be seen as the result of more than ten years research at the Institute of Mechanics (now Institute of Dynamics and Vibration) at the University of Hannover (now Leibnitz University Hannover). Again I have to thank Prof. Dr.-Ing. habil. Karl Popp for the good collaboration and his support. He passed away in April 2005 and therefore I would like to dedicate this book to him.

Furthermore I would like to thank the “Deutsche Forschungsgemeinschaft (DFG)” for the financial support of the project of the “Forschergruppe: Dynamische Kontaktprobleme mit Reibung bei Elastomeren”. Regarding Chapter 3.6 I have to acknowledge Dr.-Ing. Markus Lindner, Dipl.-Ing. Patrick Moldenhauer and Dipl.-Ing. M. Wangenheimof of the Institute of Dynamics and Vibration, Leibnitz University Hannover, for their work done with regard to the friction characteristics of rubber. With regard to the results presented in Chapter 6.10 dealing with the instationary rolling contact I have to thank Dipl.-Ing. Florian Gutzeit.

Furthermore I have to thank Dr. Jaroslaw Szwedowicz, ABB Turbo Systems, Baden, Switzerland, who carried out spin pit tests with regard of bladed disc assemblies with shrouds to validate the developed method as presented in Chapter 5.

The numerical investigations in chapter 5.4 due to the multi-coupling of bladed disc was supported by the “Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV, Frankfurt)” and was sponsored by the “Bundesministerium für Wirtschaft (BMWi)” through the “Arbeitsgemeinschaft industrieller Forschungsvereinigungen e.V. (AiF, Köln), (AiF Nr. 12565)”. Here, I have to thank the corresponding working group and the chairman Dr.-Ing. Karl Urlichs, Siemens Power Generation AG, Nürnberg for the good collaboration.

The application of the theory to a system with extended friction contacts was carried out by Dipl.-Ing. Alexander Genzo, Volkswagen, Wolfsburg. I have to thank him for this investigation presented in Chapter 5.5 and Volkswagen for their support.

Furthermore I would like to thank Dipl.-Ing. Ingo Kaiser, German Aerospace Center (DLR), Wesseling for his support in the application of the developed module to calculate the wear of railway wheels as presented in Chapter 6.9.

Last but not least I would like to thank my wife Ursula and my children Marvin and Rocco for their moral support in writing this book.

Graz, 2006 Walter Sextro

Contents

1 Introduction

1.1 Problem Description

Friction is the resistance against sliding and, therefore, friction plays an important role in dynamical engineering systems. In (Moore 1975) the mechanisms of friction are reviewed in a rich literature and the components of dry friction are summarized in (Seireg 1998) as follows:

- *Mechanical interlocking* due to the surface roughness, which leads to a higher static friction coefficient, compared to the sliding friction coefficient and explains the dynamic friction force as the force to lift off the contacts of the upper surface over the contacts of the lower surface.
- If the developed pressure at discrete contacts results in local *welding*. Due to relative motion, the welded surfaces are *sheared*. *Ploughing* of the harder material through the softer material contributes to the friction forces as well.
- *Molecular attraction*, which attributes to frictional forces and to energy dissipation, if atoms are plucked out of the attraction range,
- and for completeness, the *electrostatic forces* between the surfaces.

On the one hand, there exist dynamic systems, where friction has to be minimized, so that wear is reduced and the lifetime as well as the efficiency of a dynamic system is increased. Due to friction and wear the economic loss is estimated by five percent of the gross national product, see (Persson 1994). Hence, reducing friction and wear saves money. On the other hand, friction is used to transmit forces or to reduce vibration amplitudes, see (Popp 1994). A possibility to reduce the vibration of a machine is to use friction contacts to dissipate energy. The reduction of vibration amplitudes results in a reduction of alternating stresses and furthermore in an increase of lifetime and safety. The main part of the dissipated energy is transferred to heat. Dependent on the vibration frequencies the noise development can be reduced as well. From here, there is a need for efficient calculation procedures to optimize the dynamics of systems with friction contacts (Wriggers and Nackenhorst 2006). Before summarizing the main features of an elastic contact with friction, some important machines and machine components are presented, where friction plays an important role.

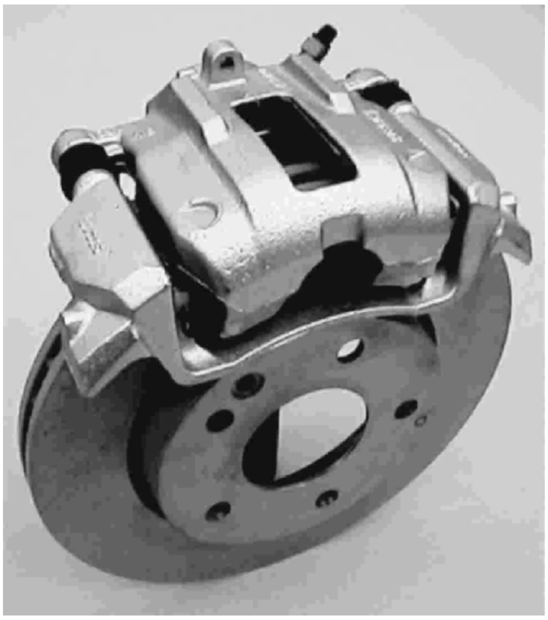

Fig. 1.1-1 Brake system (Lucas, Germany)

Brakes

Brakes are used to transmit forces to reduce the velocity of a vehicle, see **Fig. 1.1-1**. Dependent on the friction characteristic stick-slip vibration and, in extreme, a squealing noise can occur. One reason for the squealing noise is that, if the friction coefficient reaches a certain value, the brake system will become unstable, see also (Ibrahim 1994; Wallaschek et al. 1999; Allgaier et al. 1999). With respect to brakes, the manufacturing industry is not only interested in reducing the squealing noise, but also in reducing the temperature development within brakes. Otherwise, cooling devices would have to be installed. In general, the friction and therefore the dynamical behavior of brakes is very sensitive on the presence of moisture.

Machine Tools

A machine tool with friction is, for example a grinding machine, shown in **Fig. 1.1-2**, where friction plays an important role to develop smooth surfaces. The worn particles have high temperatures since they are red-hot. During grinding, it is common to use cooling fluid to remove worn material from the grinding disc, to reduce the temperature of the workpiece and the possibility of surface-burn and, hence, to increase the surface quality. Dependent on the system parameters machine chattering can occur. In this case, so-called chatter marks on the workpiece are found. Up to now, the occurrence of chatter vibrations as well as surface-burn is not understood in full detail. But there are hints, that chatter vibrations belong to friction-induced vibrations, see (Schütte and Heimann 1998).

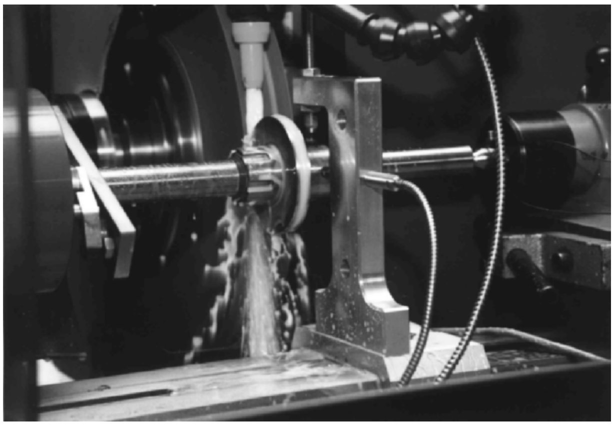

Fig. 1.1-2 Grinding machine

Motors

On the one hand, friction and wear problems between piston and cylinder of a motor are still a dynamic contact problem, see **Fig. 1.1-3**. The oil acts as a lubricant within the contact regions and reduces friction and wear. On the other hand, the calculation of the dynamics of chains is a typical problem of solving a multibody and multicontact system. Since many components are connected to each other in a motor, friction damping could be used to reduce the noise as well as the alternating stresses. Looking at the motor in full detail, there exist a huge potential to increase the lifetime of motor components, if the corresponding calculation methods are available, to optimize the system behavior.

Fig. 1.1-3 Motor (BMW, Germany, http://www.bmw.com/)

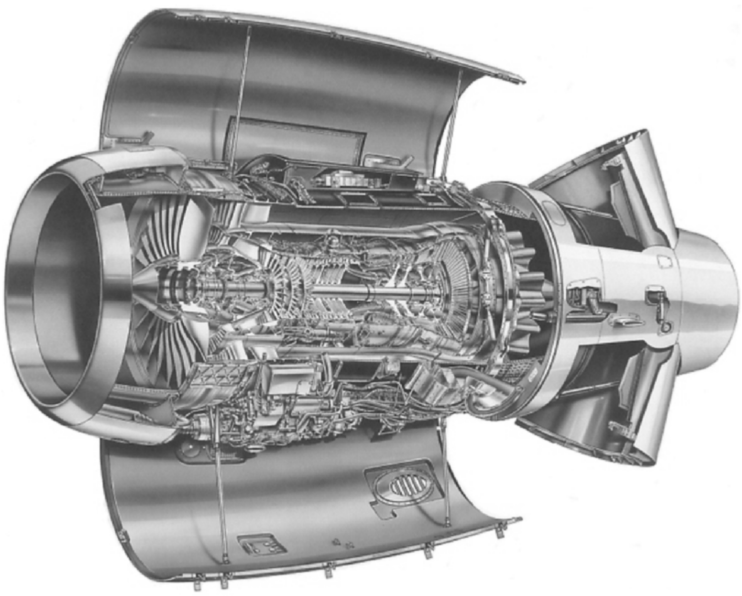

Fig. 1.1-4 Turbine (Rolls Royce, England, http://www.rolls-royce.com/)

Turbines

Turbine blades, see **Fig. 1.1-4**, are excited by fluctuating gas forces. To increase the lifetime of the turbine blades, friction is introduced to dissipate the vibration energy. Additionally, friction contacts are designed between adjacent blades or between the disc and the blades. The relative displacement of the contacting components and dry friction is used to dissipate energy and, hence, to reduce the vibrations amplitudes, noise and alternating stresses. Since a bladed disc assembly is a very large dynamical system, efficient contact models have to be developed for optimizing theses structures.

Bearings

To increase the efficiency of slide and ball bearings, see **Fig. 1.1-5**, the bearing friction has to be lowered and, therefore, lubrication is used. For example, the oil film on the ball bearings reduces friction forces because a part of the normal force is carried by the hydrodynamic forces developed by the oil film. Therefore, the hydrodynamic forces in the contact will decrease the friction and, hence, the wear. Again, for this multibody and multicontact problem with friction, there is a need for fast calculation algorithms to determine, for example, the longtime behavior of ball bearings in connection within the surroundings.

Fig. 1.1-5 Ball bearing (SKF, Germany)

Wheel-Rail Systems

The wheel-rail contact is a typical example for friction used to transmit forces, see **Fig. 1.1-6**. The contact behavior depends on the material properties of the contacting bodies. Also, the macroscopic geometry and the roughness of the surfaces influence the dynamical behavior of the system. The development of heat within the rolling contact influences the tangential contact forces as well. Here, the development of wear can lead to unround wheels, which increases the cost of maintenance and the generation of noise. Since wear is a longtime phenomenon, fast calculation procedures have to be developed to solve this problem.

Fig. 1.1-6 Wheel-rail contact (ISB, University of Hannover, Germany)

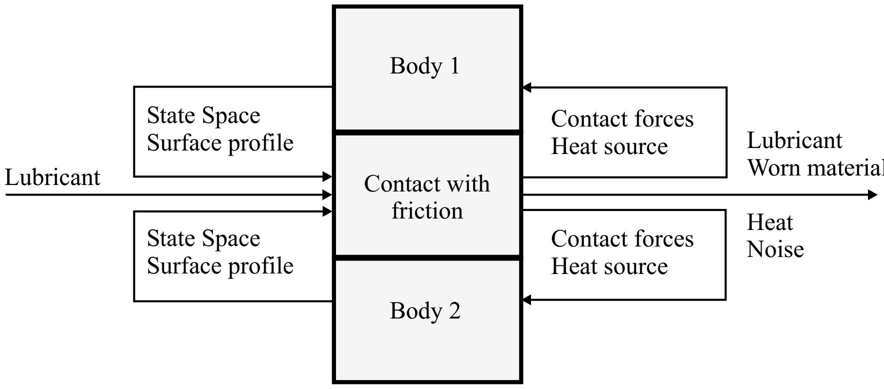

Fig. 1.1-7 Elastic contact with friction

All friction problems described above can be summarized as shown in the flow chart of **Fig. 1.1-7**. Two bodies, which can have different surface profiles and different materials, are in contact with each other. In general, both bodies can vibrate and move spatially, which is described by displacements and velocities of both elastic bodies in the so-called state space. Friction is always correlated with the development of wear and heat. The development of wear influences the surfaces profiles. The modified surfaces have an effect on the normal pressure distribution within the contact and therefore onto the dynamical behavior.

The heat generated and the temperature distribution within the bodies affects the material parameters and thus the contact forces, which can change the dynamics of the whole system. If the temperature is high enough, material transformation like oxidation can occur at the surfaces, which results again in different contact parameters and hence, will influence the contact and friction forces. Besides the contact forces, the worn material can act as a lubricant on both structures, which can reduce the friction forces. The lubricant and the worn material are defined to be the so-called third body. The output of the contact with friction is the worn material, lubricant, heat and noise.

1.2 Review

Friction contacts can be distinguished with respect to the following properties, see (Popp 1994):

- size of the contact area relative to the structure: local or expanded,
- type of normal contact force: static or dynamic,
- condition in normal direction: Hertzian or non-Hertzian,
- motion in tangential direction: micro- or macroslip.

Therefore, within the literature there exist a large number of different friction contact models.

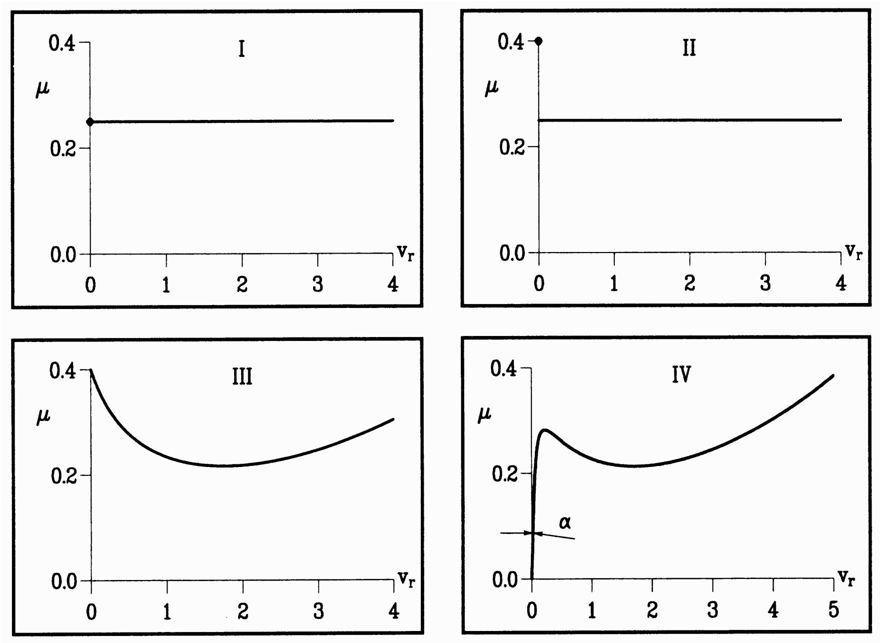

Fig. 1.2-1 Friction coefficient characteristics (Hinrichs 1997a) **I**) Coulomb friction characteristic **II**) Coulomb-Amontons friction characteristic **III**) Identified friction characteristic **IV**) Smoothened friction characteristic

Dependent on the above described properties of the friction contact, different friction contact models and solution methods are used, see for example (Johnson 1989), (Aliabadi 1993, 1995, 1997), (Gaul and Brebbia 1999) and (Gaul and Nitsche 2000). Detailed historical reviews are presented in several publications, see (Hinrichs 1997a), (Feeny et al. 1998) and (Seireg 1998). In the following, we will focus on dynamical contact problems with friction in the fields of:

- Multibody Systems,
- Continuum Mechanics and
- Finite Element Methods.

A *Multibody Systems* is built-up by springs, dampers and rigid bodies, see (Schiehlen 1990; Schwertassek and Wallrapp 1999; Shabana 2005). Within these systems, dynamic contact problems with friction are modeled by using non-smooth functions, see (Hinrichs 1997a), (Pfeiffer and Glocker 1996, 1999), (Wösle 1997), (Oestreich et al. 1996, 1998), (Brogliato 1999) and (Fidlin 2006). An overview on non-smooth systems with friction is given in (Popp 1998). To describe the dynamical behavior in the normal direction with respect to the contact surface, for example Newton's classical non-smooth impact law is used. This contact law combines the velocities before and after the impact in normal direction using a kinematic condition.

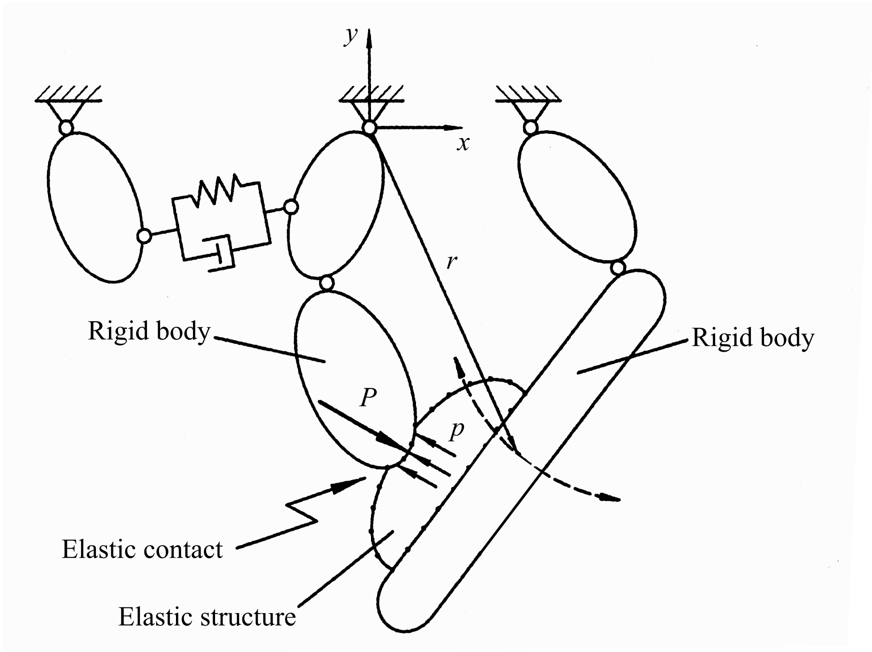

Fig. 1.2-2 Elastic Multibody System (ADAMS User Manual)

To describe the tangential contact problem the well-known, non-smooth friction characteristic developed by Coulomb in 1785 is used very often, see **Fig. 1.2-1 I**. With respect to the kinematics one distinguishes between sticking, which corresponds to zero relative velocity, $v_r=0$, and sliding, $v_r>0$. The friction coefficient μ is assumed independent on the contact area and the friction force acts opposite to the relative velocity. The normal contact and friction forces are applied in a single point. In case of sliding, the friction force is proportional to the normal contact force. Multibody systems including non-smooth friction and impact laws lead to structural variant equations of motion, which means, that the degrees of freedom of the investigated system change with time. Pfeiffer and Glocker (1996) developed a theory, using complementary equations, to handle this kind of problems, where many rigid bodies are involved.

In **Fig. 1.2-1 II**, the non-smooth so-called Coulomb-Amonton friction characteristic is shown, where the friction coefficient due to sticking, is larger than for sliding. In (Hinrichs 1997a) and (Kammerer 1998), the expanded friction contact is reduced to a point contact, where the normal force is assumed to be static.

In (Stelter 1992), the used friction law is nonlinear dependent on the relative velocity and is approximated by spline functions based on identified values of the friction coefficient, see **Fig. 1.2-1 III**. This functional behavior of the friction coefficient with respect to the relative velocity is often called Stribeck-characteristic. Further characteristics and their physical motivation can be found in (Kragelski et al. 1982).

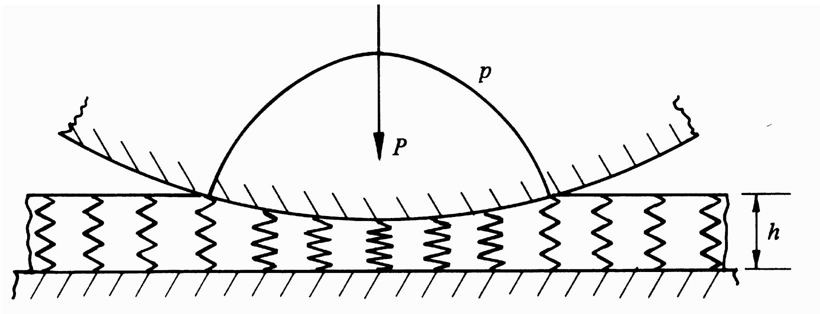

Fig. 1.2-3 Elastic foundation model (Johnson 1989)

By using smoothing function, for example the *arctan*-function, see (Popp et al. 1995), the slope at zero relative velocity has a finite value, see **Fig. 1.2-1 IV**, whereby the friction characteristic is now differentiable. Then, the non-smooth system equations can be transferred to structural invariant ones, which can be solved by standard numerical integration methods or special solvers for stiff differential equation, see for example (SIMULINK 1999).

The assumption of a rigid body corresponds to a simplified model of the real system, which is in general elastic. In extreme, the rigid body assumption and a non-smooth description of the contact can lead to a non-existent solution of the system equations, see (Glocker 1995). The non-existence of a solution is a hint, that the system is not modeled in a sufficient way. This problem can be overcome, if elastic deformations are modeled within the contact regions. In **Fig. 1.2-2**, a so-called *Elastic Multibody System* with one elastic contact is depicted. Applying for example the elastic foundation model developed by Winkler in 1867, see **Fig. 1.2-3**, a more detailed description of the reality is possible, since the contact time is finite. This simple elastic contact layer allows local deformations. Due to a cylindrical rigid body, the normal pressure distribution p is parabolic because of the linear springs of length h, see (Johnson 1989).

Within elastic multibody systems continuous structures can be approximated by so-called superelements, see (Dragos 2000), built-up by rigid bodies, springs and dampers. An alternative method to reduce the number of degrees of freedom of the continuous structures is the modal description, see for example (Hurty 1960, 1965) and (Schwertassek and Wallrapp 1999). Here, the spatial dynamical behavior of the elastic structures can be considered and described by the eigenvectors, eigenfrequencies and modal damping. These modal parameters can be for example identified by an experimental modal analysis, see (Ewins 1986).

The basis for the contact model used in *Continuum Mechanics* is the so-called elastic half-space assumption. In many cases, the contacting bodies are large compared to the contact area. Then, it can be assumed, that the contacting bodies are infinitely large, which corresponds to the elastic half-space assumption.

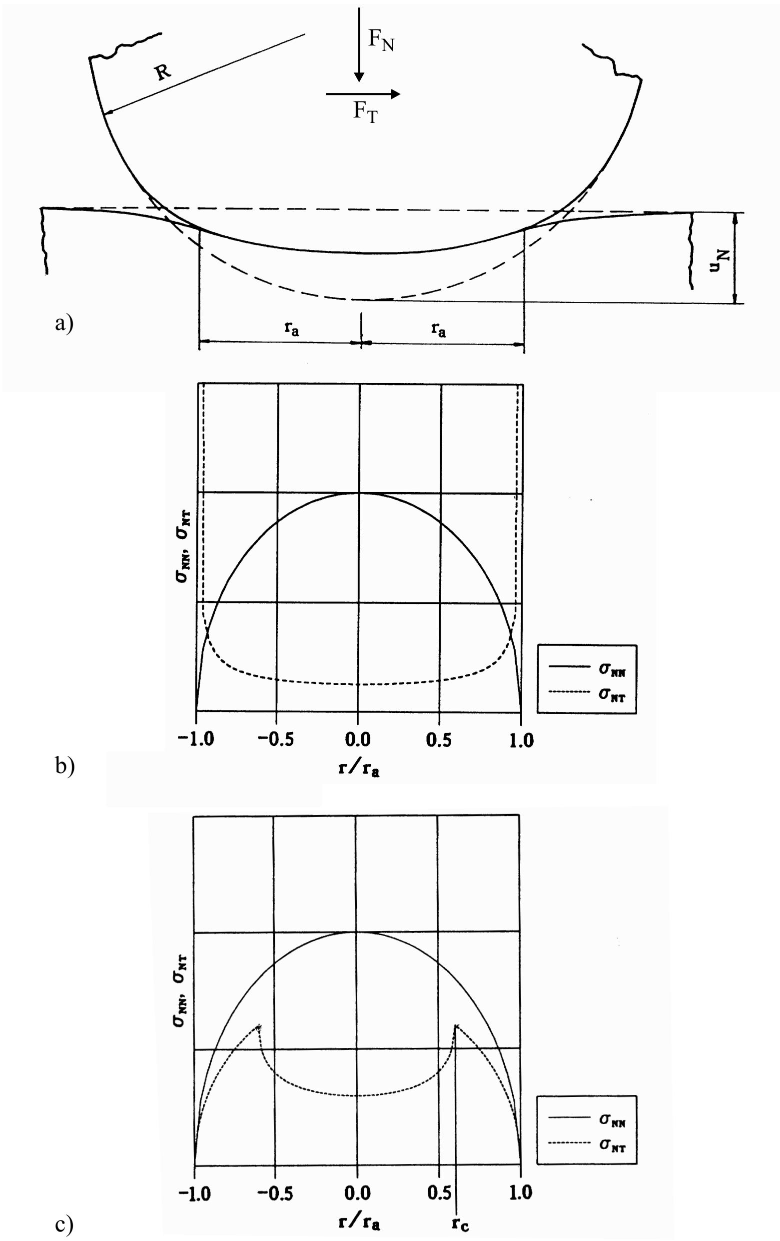

Fig. 1.2-4 **a**) Hertzian normal contact of an elastic ball contacting an elastic half-space
b) Normal pressure σ_{NN} and tangential traction σ_{NT} due to an infinite friction coefficient
c) Normal pressure distribution and tangential traction due to a finite friction coefficient