On interface modeling with emphasis on friction

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TRITA – MMK 2006:08
ISSN 1400-1179
ISRN/KTH/MMK/R-06/08-SE

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Licentiate thesis

Academic thesis, which with the approval of Kungliga Tekniska Högskolan, will be presented for public review in fulfilment of the requirements for a Licentiate of Engineering in Machine Design. The public review is held at Kungliga Tekniska Högskolan, Brinellvägen 83 Stockholm, room A425, at 9.00 on May 19, 2006.
Abstract

The general trend toward increased use of computer models and simulations during product development has led to a need for accurate and reliable product models. The function of many products relies on contact interfaces between interacting components. To simulate the behavior of such products, accurate models of both components and interfaces are required. Depending on the purpose of the simulation, interface models of different degrees of complexity are needed. In simulation of very large systems with many interfaces, it might be computationally expensive to integrate detailed models of each individual interface. Condensed models, or abstractions, that describe the interface properties with a minimum of degrees of freedom are therefore required.

This thesis deals with mechanical interfaces with an emphasis on friction. In the four appended papers friction models are discussed in terms of condensed models, as well as in terms of more detailed contact models. The aim is to study how friction can be modeled in behavioral simulation of products and to discuss the convenience and relevance of using different types of friction models as building blocks of a system model in behavioral simulations.

Paper A presents a review of existing condensed friction models for sliding contacts under different running conditions and discusses the models from both simulation and tribological points of view.

In papers B and C a simplified contact model, called the elastic foundation model, is used to model friction in a boundary-lubricated rolling and sliding contact. The model is integrated in a dynamic rigid body model of a mechanical system, the system behavior is simulated, and the result is compared with experimental results.

Paper D discusses the application of the elastic foundation model to rough surface contact problems and investigates how the error in the elastic foundation results depends on surface roughness.

Keywords: Interface model; Contact; Friction; Simulation; System behavior; Surface roughness; Elastic foundation
Preface

The research presented in this thesis was carried out between April 2004 and May 2006 in the Department of Machine Design of the Royal Institute of Technology, Stockholm, Sweden.

I would like to thank my supervisors Professor Sören Andersson, Ulf Sellgren, and Stefan Björklund for their excellent guidance and support throughout this research. I would also like to thank my ex-colleague and co-writer Christer Spiegelberg for stimulating collaboration, valuable discussions, and help.

The source of funding has been the Swedish Foundation of Strategic Research (SSF), as a part of the project INTERFACE within the national Swedish research program ProViking.

Stockholm, May 2006

Anders Söderberg
Thesis

This thesis consists of a summary and the following four appended papers:

Paper A


Accepted for publication in Tribology International

Paper B


Paper C

Anders Söderberg and Christer Spiegelberg, “Modeling transient behavior of a mechanical system including a rolling and sliding contact”, Proceedings of IMECE 2005, 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, Orlando, Florida, USA

Paper D

Anders Söderberg and Stefan Björklund, “Validation of a simple contact model and its applicability on rough surfaces”, Proceedings of 12th Nordic Symposium on Tribology NORDTRIB 2006, June 7-9, Helsingor, Denmark
Division of work between authors

The work carried out in this thesis was initiated and supervised by Professor Sören Andersson, Ulf Sellgren, and Stefan Björklund.

Paper A
Simulations were performed by Söderberg. Most of the writing was done by Andersson, but Söderberg also contributed to the writing and editing of the text.

Paper B
System modeling and simulations were performed by Söderberg. Spiegelberg provided the contact model integrated in the simulations. Experimental work was equally divided between the authors. Most of the writing was done by Söderberg, but Spiegelberg contributed.

Paper C
System modeling and simulations were performed by Söderberg. Spiegelberg provided the contact model that was integrated in the simulations. Experimental work was equally divided between the authors. Most of the writing was done by Spiegelberg, but Söderberg contributed.

Paper D
Work and writing were mainly performed by Söderberg. Björklund provided the reference model and supervised.
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### Appended papers

A. “Frictions models for sliding dry, boundary and mixed lubricated contacts”

B. “Simulation models of test equipment for measuring transient friction in a rolling and sliding contact”

C. “Modeling transient behavior of a mechanical system including a rolling and sliding contact”

D. “Validation of a simple contact model and its applicability to rough surfaces”
1 Introduction

The general trend toward increased use of computer models and simulations during product development has led to a need for accurate and reliable product models. In many aspects modern products can be viewed as technical systems, i.e., sets of subsystems or machine elements interrelated to each other and to the whole so as to achieve a common goal. Most subsystems are an assemblage of elementary machine elements, and therefore both subsystem and machine elements will here be called “components”. The function of a component, and ultimately of the whole system, often relies on physical interactions at mechanical interfaces within the component or between the component and surrounding components or environment.

With today’s computer-based modeling and simulation techniques the behavior of single part components can be simulated rather well and accurately, but complex technical systems in which the components are connected by mechanical interfaces still cannot be directly modeled and simulated with reliable results. Another way to see this problem is to note that interior properties such as structural strength and fluid flow can be predicted relatively well, but surface properties such as friction and wear cannot. Consequently, one way to obtain more accurate and reliable simulations of complex technical systems is by developing models that describe the characteristics of mechanical interfaces under different conditions. These models should address a number of different aspects such as contact stiffness, damping, friction, wear, etc.

This thesis deals with the modeling and simulation of mechanical interfaces with an emphasis on friction. It consists of this summary and four appended papers that discuss the issue from both simulation and tribological points of view. Their common aim is to study how friction can be modeled in behavioral simulation of technical systems and to discuss the convenience and relevance of using different types of friction models as building blocks of a system model in simulations.

Paper A presents a review of existing friction models for sliding contacts under different running conditions.

In papers B and C a simplified contact model, called the elastic foundation model, is used to model friction in a boundary-lubricated rolling and sliding contact. The model is integrated in a dynamic rigid body model of a mechanical system, and the system behavior is simulated.

Paper D discusses the application of the elastic foundation model to rough surface contact problems and investigates how the error in its results depends on surface roughness.
2 Interface models

The research presented in this thesis has been performed as a part of the INTERFACE project. The project draws on the work done by Sellgren [1][2] who developed general principles for modeling systems. His approach is modular and lays down strict guidelines for behavioral models of machine elements, modules, and interfaces. Sellgren defines an interface as an attachment relation between two mating faces.

The modeling principle proposed by Sellgren is illustrated by the link mechanism of the lifting system shown in Figure 1. The different components of the mechanism are represented by CAD models, and the interfaces are represented by symbols from $i1$ to $i6$. An interface can be both a mechanical contact and an interface element, as when it is a bearing or a system component such as a coupling. The models of these interfaces can be seen as transfer functions describing the relation between flow and effort parameters of both sides of the interface. Depending on the purpose of the simulation, interface models of different degrees of complexity are needed. In simulation of very large systems with many interfaces, it might be computationally expensive to integrate detailed models of each individual interface. Condensed models, or abstractions, that describe the interface properties with a minimum of degrees of freedom are required.

This thesis considers interfaces in the sense of mechanical contacts and focuses on models describing the friction in these contacts. Friction in mechanical contacts is influenced by many parameters, including the geometry of the contact surfaces, their properties, the running conditions, and any lubricants used. In this case a detailed interface model can be a contact model used to evaluate the deformation and stresses of the two surfaces, whereas the corresponding condensed model can be an empirical expression for evaluation of the friction force without detailed knowledge of the local contact conditions.

![Figure 1 Mechanical components and interfaces in a model of a wheel loader lifting unit. The interfaces are marked with rings and indexed i1 to i6 (From Sellgren [2]).](image)
3 Nature of friction

When two solid bodies in contact are subjected to applied forces that tend to produce relative sliding motion, stresses develop on the interfaces that tend to oppose that motion. The phenomenon is called friction and is often discussed in terms of the resultant of the stresses, the so-called friction force. Friction phenomena have been of interest for a long time. The classic friction laws discussed in most textbooks on the subject (e.g., [3]) can be traced back to the fifteenth-century scientist Leonardo da Vinci, although they are often attributed to Amontons and Coulomb, who published their work in the seventeenth and eighteenth centuries, respectively. The classic friction laws apply to nonlubricated contacts between metallic bodies and can be summarized as:

- The friction force is independent of the apparent area of contact.
- The friction force is proportional to the normal contact force.
- The friction force is independent of the sliding velocity.

The first two laws are generally observed to hold for gross motions, but the third law is known to be invalid [4]. However, for many purposes in which only limited velocity ranges are of interest the friction can be assumed to be constant in the studied range.

It is hard to understand how friction arises without knowing how surfaces interact when brought in contact. It is well known that real engineering surfaces are not perfectly smooth. Even highly polished surfaces possess roughness at some scale. Because of roughness, only a part of the surfaces are actually in contact; see Figure 2. The most widely accepted theory of the mechanisms of friction between metallic surfaces is presented by Bowden and Tabor [5]. Their theory states that the friction in contacts between metallic bodies is mainly due to two causes: shearing of metallic joints between the surface asperities and the plastic deformation of the softer surface by harder asperities.

![Figure 2](image)

Figure 2 Contact between engineering surfaces. (a) Schematic figure of local contact between surface asperities. (b) The concepts of apparent and real area of contact exemplified by the contact between a smooth ball and a rough plane.
The common measurement of sliding friction is the coefficient of friction, i.e., the ratio between the friction force and the normal contact force. Often two values of the coefficient of friction are quoted: the coefficient of static friction, which applies to the onset of sliding, and the coefficient of kinetic friction, which applies during sliding motion. In most cases the static coefficient is known to be higher than the kinetic coefficient. Because the friction between sliding contact surfaces is a result of stochastic interactions between rubbing asperities, the friction force in nearly all friction tests is highly stochastic in nature and the coefficient of kinetic friction is often taken as a mean value.

Although not universally applicable, the classic laws of friction give a basic understanding for nonlubricated contacts. However, many mechanical interfaces in engineering applications are lubricated, and in lubricated contacts the friction is known to show a velocity dependence. This behavior is often described with the curve shown in Figure 3. This curve is named after Stribeck, who first studied these phenomena in the early twentieth century [6]. The form of the Stribeck curve is often explained by defining different regimes of lubrication (e.g., [3]). At low velocities the hydrodynamic pressure buildup in the contact is negligible and the contact load is assumed to be transmitted mainly by mechanical contact between the asperities. This lubrication regime is referred to as boundary lubrication. In the mixed-lubrication regime the contact load is divided between asperity contacts and the lubricant. Consequently, the friction in the contact is partly due to asperity interactions and partly due to the shear stresses in the lubricant. In the full film regime the surfaces are completely separated by the pressure buildup in the lubricant and the friction corresponds to the shear stresses in the lubricant.

Figure 3 Schematic Stribeck curve and the different lubrication regimes (BL – boundary lubrication, ML – mixed lubrication, FL – full film lubrication).
The classic friction laws only consider bodies sliding relative to each other, but deformations and local sliding will occur in the contact interface before global sliding can be observed [7]. This phenomenon, called microslip, is believed to be caused by elastic and plastic deformation of the surfaces combined with local sliding in the contact. The contact interface can be considered to be divided into zones in which the bodies stick together and slip zones in which they slide against each other. The amount of slip in the contact increases with the tangential load until gross slip is obtained and the whole contact interface is sliding. Microslip has a strong influence on the contact stiffness and damping in apparently static contact interfaces such as screw joints. Both the tangential contact stiffness and the length of the microslip zone are affected by the surface roughness [7]. Microslip can be found in sliding contacts as well as in rolling contacts. Rolling contacts with microslip are often referred to as rolling and sliding contacts.

![Schematic tangential load–displacement curve for an oscillating sliding contact with microslip](After Hagman [7]).
4 Condensed friction models for sliding contacts

Knowing something about the mechanisms behind friction, we can turn to the question of how friction can be modeled in behavioral simulation of mechanical systems. We will start by discussing condensed models useful for direct evaluation of the friction force between the interacting surfaces. The discussion is based on the findings of paper A, which presents a review of different friction models for sliding contacts under different running conditions. The purpose is not to give a complete review of all existing friction models, but rather to give insight into what possibilities are offered. Other reviews on friction models have been presented by Oden and Martins [4] and by Olsson [8]. In paper A the models are expressed as equations describing the friction force, but they could be reformulated as relations describing the coefficient of friction if preferred. The models are empirically based and must be calibrated to experimental data to be considered valid for a specific contact. Yet while the friction force in nearly all friction tests is highly stochastic in nature, with significant variations in both amplitude and frequency, most friction models do not take these variations into account and instead represent the friction forces by a smooth mean value.

![Figure 5 Examples of different friction models. (a) Coulomb friction model. (b) Stribeck friction model. (c) Coulomb friction model where a tanh function is used to model the transition from negative to positive sliding velocity. (d) Dankowicz friction model.](image)

> Figure 5 Examples of different friction models. (a) Coulomb friction model. (b) Stribeck friction model. (c) Coulomb friction model where a tanh function is used to model the transition from negative to positive sliding velocity. (d) Dankowicz friction model.
The most commonly used friction model is the so-called Coulomb friction model, which is based on the classic laws of friction. Although it is known that a Coulomb friction model does not always represent the friction behavior in a contact well, such models are often used to describe the friction in mechanical contacts. The model is used for nonlubricated contacts as well as boundary and mixed lubricated contacts. An improved model for lubricated contacts can be obtained by substituting the constant Coulomb friction force with a velocity-dependent function describing the Stribeck curve. Here this type of model is referred to as the Stribeck friction model.

From a simulation point of view, the main disadvantage of the Coulomb and Stribeck friction models is the undetermined friction force at zero sliding speed. These friction models run into problems at the start of a motion and at the point where the motion reverses. Although the behavior at these points can be modeled by a sign function, which represents the behavior fairly well, the representation complicates simulations and necessitates extra condition checks of the system states or interruptions of the simulations. Various tricks can be used to overcome the problem, such as replacing the sign function with a more appropriate continuous function, e.g., the tanh function. These modifications improve the ability of friction models to simulate the behavior of systems, but they do not represent small displacements very well. Small displacements, or microslip, are important in many high-precision and -control applications, and therefore models that can handle microslip are needed.

Attempts to construct friction models that incorporate microslip are often based on the assumption that friction is a function of the contact surfaces’ displacements. More than 50 years ago Mindlin presented a theoretical model for microslip in elastic contact between two spheres [9]. More recently, theoretical models for microslip in contacts between nominally flat surfaces have been presented by Olofsson and Hagman [10] and Björklund [11]. To incorporate the energy dissipation in oscillating contacts, most microslip models use different relations between friction and displacement for loading and unloading of the contact. This requires extra condition checks of the system state to decide which relation to use, and therefore these models are unsuited for implementation in dynamic simulations. Both Dahl [12] and Dankowicz [13] have proposed models with a more convenient way of dealing with the problem. In their models the level of microslip in the contact interfaces is modeled by a first-order differential equation. In paper A it is shown that these models behave as linear springs at small displacements, which can lead to undamped high-frequency oscillations in the friction force. This behavior suggests that there is no sliding whatsoever in the contact, just elastic deformation. Theoretically there would exist local sliding at any tangential load, no matter how small, leading to energy dissipation and damping. Canudas de Wit et al. [14] propose a model similar to the Dahl and Dankowicz models that include a damping term coupled to the time rate of the microslip to give energy dissipation even at very small displacements. Furthermore, the model proposed by Canudas de Wit et al. incorporates Stribeck effects and thus gives the possibility of modeling contacts running under different conditions.
5 Modeling friction with detailed contact models

So far, only models giving an expression for the total friction force have been discussed. In some cases, these condensed models do not give enough information about the friction in the contact and more detailed models are needed to analyze the local stresses and deformations in the contact interface. The use of a more detailed contact model also allows the incorporation of other contact phenomena such as wear and temperature effects that may significantly influence the friction in the contact.

Stresses and deformations in nonlubricated and boundary-lubricated contacts can be modeled by using knowledge and methods from the research field of contact mechanics. There exist analytical solutions to only a very limited class of contact problems. For a general contact problem stresses and deformations in the contact interface can be computed numerically with FEM, the finite element method, or BEM, the boundary element method. The contact is then discretized into elements, and the stresses and deformation are calculated for each element. For accurate results nonlinear elastic and plastic material behavior and finite friction should be included in the model. These issues can be taken into account in the numerical solution, but the price to pay is that it becomes computationally demanding. The use of this type of model in dynamics system simulations where repeated contact computations are needed will lead to highly time-consuming simulations. Hence, computationally efficient contact models are required, and depending on the purpose of the simulation, simplified and less accurate models can be preferable to more accurate, but also more complex, models.

One of the things that makes most numerical contact models time consuming is the fact that the deformation at one point in the contact will be influenced by the stresses and deformation at all other points. A fast, but approximate, method for calculating the pressure distribution, referred to as the Winkler elastic foundation model, is to ignore this mutual influence between different points in the contact. A similar approach, often called the brush model, can also be used for tangentially loaded contacts. The fundamentals of both methods are described by Johnson [15]. A contact model based on the above methods, referred to as the elastic foundation model, is discussed in papers B, C, and D. The model only considers elastic surface deformations, and local friction is modeled by a Coulomb friction model.

Because the mutual influence between surrounding points is ignored, the elastic foundation model gives only an approximate solution to the contact problem. To be considered valid for a specific contact the parameters of the elastic foundation model must be inversely modeled, i.e., calibrated. For many nonconformal contacts between smooth surfaces this can be done by comparing the results of the elastic foundation model with analytical solutions for known standard cases [16]. For other more complex contacts detailed FEM- or BEM-based contact simulations could be used as independent references. Because of its inherent nature, the results of the elastic foundation model cannot correspond to all aspects of the reference solution at the same time. Which aspect
of the contact is most relevant, e.g., area of contact, stiffness, or pressure, depends on the purpose of each specific simulation.

Papers B and C focus on analysis of systems containing boundary-lubricated rolling and sliding contacts using the elastic foundation model. The elastic foundation model is integrated into a dynamic rigid body model of a mechanical system to improve the accuracy of behavioral simulation. The mechanical system that is modeled and simulated is test equipment for studying a rolling and sliding contact between two discs; see Figure 6.

In paper B two different system models are constructed; one where the microslip in the contact between the discs is neglected and one where the elastic foundation model is integrated. Simulation of the system behavior is performed with both models, and the result is compared with experimental observations. The mechanical system proved very sensitive to changes of the contact conditions. Thus integration of the contact model is needed to construct a system model that is valid for a wide range of running conditions. Integrating the contact model in the system model increases the complexity of the model and leads to increased computational time.

Paper C discusses in more detail how the contact conditions influence the mechanical system presented in paper B. Simulations are performed with the system model that includes the elastic foundation model. As in paper B, the result is compared with experimental observations. Through simulations, how the surface roughness may influence the system is also investigated. Simulations are made with smooth as well as rough contact surfaces. If the contact surfaces are modeled as smooth, the tangential stiffness of the contact model must be set to a lower value than that suggested in the literature to get correlation with experimental results. The simulations also indicate that the roughness of the contact surface may cause disturbance of the system behavior.

![Figure 6 Test equipment simulated in papers C and D](image-url)
Surface roughness tends to have a significant effect on how loads are transmitted at the contact interface between solid bodies. Therefore, it is desirable to include surface roughness in detailed contact models. A problem encountered when solving problems of rough surfaces is that the surface elements must be small enough to allow the effect from individual surface irregularities to be included in the solution. This means that when the nominal contact area is large compared to the surface features of interest, the necessary number of elements becomes too large for a reasonable computational effort. Here also the elastic foundation model has advantages because it is faster to evaluate and thus allows a higher element density.

Because of the simplifications done in the elastic foundation model, the applicability of the model in numerical analysis of rough surfaces can be questioned. This is addressed in paper D, which discusses how surface roughness influences the errors in the elastic foundation solution if the parameters in the elastic foundation are set to give correspondence between the elastic foundation solution and analytical solutions assuming smooth surfaces. This is done by comparing the elastic foundation model's results with those of a more accurate contact model that takes the mutual influence into account [17]. First, the normal contact between a smooth sphere and a rough plane is investigated. Thereafter a tangential load is applied, and the tangential traction in the contact is evaluated. The solutions obtained with the two models are compared in terms of predicted pressure distribution, real contact area, and normal and tangential contact stiffness. The results presented in paper D can be used to estimate the extent of error in the elastic foundation model, depending on the degree of surface roughness. The main conclusion is that the results of the elastic foundation model do not agree well with those of the reference model regarding predicted real contact area and maximum pressure. The estimated errors in compliance and initial tangential stiffness are considerably lower, which indicates that the model can be useful for predicting the contact stiffness, but not obviously for predicting the detailed contact state.
6 Concluding remarks

The function of many technical systems relies on contact interfaces between interacting components. To simulate the behavior of such systems, accurate models of both components and interfaces are needed. This thesis deals with the modeling and simulation of mechanical interfaces with an emphasis on friction. In the four appended papers friction models are discussed in terms of condensed models for direct evaluation of the total friction force, as well as in terms of more detailed contact models for evaluation of the stresses and deformations in the contact interface.

Although the Coulomb friction model is commonly used in simulation, it is known that it does not always represent the friction behavior in the contact well. Other, more appropriate models have been proposed, and paper A presents a review of different condensed friction models for sliding contacts under different running conditions. The friction in lubricated contacts running in different lubrication regimes can be modeled by a Stribeck model, and microslip can be modeled by formulating the friction model as a differential equation.

In some cases more detailed contact models are needed to calculate the friction in the contact interface. Detailed contact models have the advantage of giving more information about contact conditions, but are often complex and computationally demanding. Integrating detailed contact models in dynamic system simulation leads to time-consuming simulations and therefore fast but less accurate models can sometimes be preferred to accurate and complex models. The elastic foundation model is an example of a simplified contact model that can be used for this purpose. The elastic foundation model incorporates many major simplifications, but it is fast to evaluate and therefore has the potential to be used in simulations where repeated contact evaluations are needed. An example of this is given in papers B and C, where the elastic foundation model is integrated in a rigid body model of a technical system, used to simulate the dynamic behavior of the system.

Because of the simplifications done in the elastic foundation model, the applicability of the model to numerical analysis of rough surfaces can be questioned. The results presented in paper D indicate that the model is useful for predicting the contact stiffness but not for predicting the detailed contact state. This means that the elastic foundation model might not be accurate enough to give a correct prediction of the actual contact stresses and deformations, but it might be good enough for system dynamics simulations where contact stiffness and damping are crucial.
7 Future work

This thesis represents the first part in a research project with the long-term goal of creating a system of interface models to assist product development with behavioral simulations of technical systems. The natural way to end this summary is by discussing the possible future work to achieve this goal.

So far, the work has focused on friction phenomena, and in the future work some attention will be turned to wear modeling and simulation. Because the aim is to make it possible to use simulations to predict how friction and wear influence the behavior of technical systems, integration of interface models in behavioral analysis of technical systems will also have a natural part in the future work.

A possible work procedure would be to start by analyzing an engineering problem with a detailed numerical contact model that incorporates surfaces roughness effects, local friction, and wear. Based on the result of these simulations, simplified or more condensed models can be constructed. The work will mainly be based on modeling and simulation, but to validate the accuracy and relevance of the models some experimental work may be needed.
8 References


