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A review of continuous contact-force models in multibody dynamics

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ABSTRACT

This is a review of well established and recently introduced contact-force models that are used in the dynamical analysis of multibody systems. In particular, two contact groups have been investigated: the general (point contact) and the cylindrical (line contact) models. For the point-contacts group, 20 different models are listed and a dozen are used in numerical simulations for comparison. While for the cylindrical-contacts group 10 models are listed and most of them are compared on the basis of results of numerical simulations.

Basic numerical experiments are used to compare the evolution of the contact force during the contact process for the presented general contact-force models with energy dissipation and cylindrical contact-force models with and without energy dissipation at the contacts. The effects of the different hysteresis-damping models on the presented general contact-force models are compared. Furthermore, the cylindrical contact-force models are compared in terms of the contact force and the hysteresis damping in the contact.

The objective of this review is to offer basic guidelines for the selection of the proper contact formulation for a specific application in the analysis of multibody dynamics with continuous contacts-impact events. Twenty general contact-force models are presented in this research and more than 10 cylindrical continuous contact-force models are presented and compared. Furthermore, a hysteresis-damping effect in cylindrical contact-force models is researched and presented.

1. Introduction

Research activities in the area of multibody dynamics have increased significantly in recent decades, mainly due to the market demand for high quality products by the rapid progress in computer technology and the development of appropriate theories of dynamics that enable the modeling of dynamical systems with contacts in a variety of engineering applications, such as: civil and infrastructure applications [1–3], granular materials [4], designing parts or assemblies of mechanical systems [5–10], railway dynamics [11–14], crash analysis [15–17], bio-mechanics [18–24], robotics [25–27], mechanisms [28–32], vibro-impact drilling [33], bearing elements [34] and others [35,36]. Multibody dynamics can be categorized as the study of mechanical systems assembled from several bodies that are interconnected with kinematic constraints that restrict their relative movement and are subjected to the acting external forces [37,38]. These forces can include inertia or gravitational forces, state-dependent forces or contact forces generated by the contacts between the bodies. The intensive impact can often result in limited operation or the failure of a mechanical system due to vibration [39], load propagation [40], fatigue [41], cracks [42], wear [43] or any other cause, leading to a non-functional state.

It is important to mention that the bodies that are assembled in a multibody system can be considered as rigid or deformable. A body can be considered as rigid when its deformations are small, such that they do not affect the global motion of the body itself [44]. It is assumed that rigid bodies are a representation of actual mechanical systems, although they are not completely rigid in nature. Many mechanical systems are assembled from rigid and deformable bodies or rigid bodies with soft surfaces or bodies that are rigid enough to be considered rigid overall, although they can experience significant local deformations during the contact-impact process. Consequently, a contact-evaluation procedure must be able to model the dynamics of the contact between compliant surfaces [45].

In a multibody system impact occurs when two bodies collide [46]. The main properties of the contact-impact process are: very short durations, large contact forces, rapid dissipations of the energy and high accelerations and decelerations of the contacting bodies [47]. The continuous contact-impact process is divided into two phases: compression and restitution. At the beginning of the contact process, the start of the compression phase, the contact force increases simultaneously with the contact deformation and reaches its maximum value at the end of the compression phase. The restitution or expansion phase follows the

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compression phase, where the energy that is stored during the compression phase drives the bodies in contact apart, and it ends when the two bodies are separated. Consequently, some energy, due to internal damping [48], is lost through vibrations, heat, sound and in other forms [49]. It was found that perfectly elastic collisions between two bodies dissipate energy, due to the transformation of the initial kinetic energy into internal vibrations after contact [50]. Thus, the initially developed elastic models needed to be developed to enable the dissipation of energy during the contact-impact process. One of the most widely used concepts to consider energy dissipation is based on the use of coefficient of restitution. This parameter has different definitions and one of the most popular and commonly used is Newton's law of restitution, also known as the kinematic coefficient of restitution. It is defined as the ratio of the post-impact relative velocity to the pre-impact relative velocity of the body going through the contact-impact process. A positive value of the relative contact velocity in the normal direction between two contact points on each body indicates that the bodies are approaching, during the compression phase, and reaches a value of zero at the point of maximum contact deformation, and a negative value of the relative contact velocity in the normal direction indicates that the bodies are moving away from each other during the restitution phase.

When performing a dynamical analysis of a multibody system it is important to find an accurate time value for the transition between the different states, specifically the transition between the non-contact and the contact states. If the time value at the start of the contact is not detected properly, the initial contact force might become abnormally large due to the artificially large initial indentation between the bodies in contact. This numerical problem leads to an artificial increase in the mechanical energy of the system and can also stall the integration process. To overcome this shortcoming, close control of the numerical procedure, which automatically detects and evaluates all the initial contact situations efficiently, is required [51]. In practice, when working with numerical simulations, most of the processor time is used on contact-detection tasks. The contact between two bodies can be due to the free movement of both bodies or due to the clearances in a mechanical joint (i.e., a planar revolute clearance joint can be considered as a special type of internal contact between the two cylinders) [52–54]. Recently, a unified approach to the modeling of mechanical joints with and without clearances was introduced in the frame of multibody dynamics [55] and the effect of a 3D revolute clearance joint on the engineering application of planar mechanisms was investigated and validated based on experimental data [56]. When working on the numerical simulations of multibody systems [57,58] an experimental investigation [59–62] is also important to successfully characterize the parameters of the dynamics [32,63] or to validate the numerical results [64].

In general, the contact-impact event in multibody dynamics can be evaluated based on the continuous method, also known as the smooth approach, at the force-acceleration level [65], or based on the unilateral geometrical constraints, also known as the non-smooth approach, at the impulse-velocity level [66]. There are three main features that define these two methods: (i) the location of the contact points, (ii) the relative penetration or contact deformation between two bodies and (iii) the contact forces [67]. The contact points on both bodies are coincident, while some local deformation at the contact is allowed with the penalty method. The contact deformation represents a key value as it is used to evaluate the contact force according to the appropriate constitutive law [68].

Another approach to modeling the contact-impact event in the dynamic analysis of multibody systems, for the non-smooth approach, is based on impulse-momentum [69] theory. This has been primarily applied to impacts between rigid bodies [47]. The theory of impulse-momentum used in modeling the contact-impact event assumes that the deformation in the contact remains small in comparison to the overall geometry of the colliding bodies and that the time interval of the contact-impact process is sufficiently brief. Therefore, the potential energy of the mechanical system does not change and so there are no changes in the system configuration and all the other external forces can be considered negligible. The changes in velocity occur instantly, as a result of the large impact forces. When implementing this approach in the computer software code only a minimum penetration is allowed to detect the contact in a numerical manner and this not used to evaluate the size of the contact impulse. The energy-dissipation effect is included via the relation between the impulse of the contact force in the compression and restitution phases and the coefficient of restitution [70].

During the dynamical analysis the state variables of a multibody system during a contact-impact event can be evaluated using either a continuous or a discontinuous approach. The penalty method is the most frequently used continuous approach, where the contact forces and the deformations are modeled with a set of spring-damper elements that represent the surface compliance of the contact bodies [71]. In the non-smooth approach, the unilateral constraints are solved as a linear complementary problem (LCP) [72–76]. When the contact is considered as a contact between two cylinders based on the continuous approach, a suitable contact-force law should be used. In fact it is advisable [77] to use one of the cylindrical contact-force models summarized in this study, however other models can also be used [67,78–80].

This work focuses on presenting and reviewing different continuous contact-force models for point and line contacts that have been used in a variety of multibody applications. The evolution of both types of contacts, based on geometry, and the developed contact-force models are presented and compared. Besides the definitions, basic multibody systems are also used for the comparison of the models. The main objective of this manuscript is to provide users with a common platform where they can easily find developed continuous contact-force models, for general and cylindrical contact geometry, and compare them so as to select the most suitable continuous contact-force model. The focus is also on energy-dissipation models, which are compared for general contact force models and further discussed for cylindrical contact-force models.

This study is organized as follows. Section 2 presents the developed general contact-force models that are based on a point contact between two spheres and their comparison based on a simple dynamical system. Section 4 presents the developed cylindrical contact-force models and their comparison based on a simple dynamical system with an internal contact between two cylinders. A discussion about the integration of the dissipation in the cylindrical contact-force models is presented in Section 6. The conclusions are drawn in Section 7.

2. Review of the general contact-force models

The foundations of pure elastic contact-force models were laid by Hertz [81], who concluded that, in general, a contact area was elliptical and no energy dissipation was considered during the contact-impact process. This led several researchers to develop more advanced contact-force models that take this energy dissipation into account.

A thorough overview of general contact-force models was made by [65,67], while some cylindrical contact-force models were researched and compared by Pereira et al. [77,82]. For a greater computational efficiency of the numerical simulation and to avoid convergence problems, during each integration time step a contact-force model that represents an explicit correlation between the contact deformation and the contact force is advised [77]. This explicit correlation between the contact deformation and the contact force is defined using the Lankarani–Nikravesh contact-force model for a general contact [71,83] and has been used in several studies of rigid [84] and rigid-flexible [85] multibody systems. Recently, an enhanced cylindrical contact-force model was developed for an easier implementation in computer software codes [86], and it was also used in research of the dynamics of chain drives using a generalized revolute clearance-joint formulation [87]. The cylindrical contact-force models generally represent the contact force as an implicit function of the contact deformation and do not account for the energy dissipation during the contact process. The lack of energy dissipation