Mechanism and Machine Theory 86 (2015) 265–280

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Bond graph modeling of dynamics of soft contact interaction of a non-circular rigid body rolling on a soft material

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ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 10 December 2014
Accepted 15 December 2014
Available online 13 January 2015

Keywords:
Bond graph
Center of curvature
Contact algorithm
Soft contact

ABSTRACT

The bond graph model for soft contact interaction between a circular rigid body and a soft material has already been developed and validated experimentally in a previous work. The present work further extends the approach to soft contact interaction for non-circular rigid bodies rolling on soft material which is difficult to model otherwise. An elliptical disc is taken as the non-circular rigid body as an example. An algorithm is developed to detect nodes of the soft material which contact the disc at any time. The contact interface between the two surfaces is assumed to be viscoelastic which is the penalty approach with additional dissipation. The model is applicable for all geometries of the rigid body. The contact model also takes normal force and tangential frictional force into account. The model dynamically determines the number of contact nodes, and hence the contact area at any time as the contact interface changes. Results of simulation of the model, based on code generated algorithmically from the bond graph structure, provide better understanding of the soft contact interaction issues involved.

1. Introduction

The existing approaches for contact modeling can broadly be divided in three categories: constraint based, impulse based and penalty based approaches [1,2]. The constraint based approach uses optimization methods to compute contact forces, and is largely limited to simple geometries. The impulse based approach is suitable for modeling collision or impact contact [3], but not for a system of bodies in resting and continuous contact. Further, it is less accurate than the constraint based approach because it computes contact forces for one impulse at a time between the colliding bodies [4]. In the penalty approach, at a point of contact, a virtual linear spring is inserted which produces a force proportional to the depth of penetration, and further inter-penetration is avoided [5,6]. However the penalty approach gives approximate results. All these approaches have been applied to model the contact between two rigid bodies, but not for the soft contact. The rolling contact between a rigid circular disc and a soft material has already been modeled using multibond graph approach, and validated experimentally [7,8].

However, in the case of the circular geometry, the radius of curvature of the rigid body surface is uniform throughout; there is only one center of curvature, and it remains at the same location on the body. Normal and tangential unit vectors to the contact point can be determined easily. For non-circular geometry, center of curvature of each point on the periphery of the rigid body is different, and so is the radius of curvature.

In this extended work, the dynamics of a system comprising of an elliptical rigid disc interacting with the soft material is modeled using multibond graph approach integrated with the finite element method [9,10]. The elliptical disc is not a uniform geometry in the sense that the center and the radius of curvature vary for each point on the disc periphery.

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http://dx.doi.org/10.1016/j.mechmachtheory.2014.12.010

Initially the disc is kept on the soft material in an inclined position as shown in Fig. 1. It is then released and allowed to fall by its own weight. The contact area and the force distribution vary continuously as the disc moves on the soft material. In this work, an algorithm based on the constraint imposed by the geometry of the rigid body, is used for contact detection. Most of the contact algorithms available are based on defining the contact constraints as a linear complementarity problem (LCP). The contact forces are calculated by formulating and solving the LCP [11]. In contact problems, it is important to detect when and where contact occurs. Lopes et al. [12] solved contact detection problems considering the minimum distance between two contacting surfaces. Flores et al. [13] proposed a methodology to detect the instant of contact for an impact analysis between any pair of contact surfaces. The approach adjusts the time step in variable time-step integration algorithm on the basis of maximum allowable interpenetration. They developed a continuous contact force model with a hysteresis damping parameter that accounts for dissipation of energy during contact [14]. Machado et al. [15] presented a comprehensive study of compliant contact models for multibody system dynamics. The Hertz's elastic contact model is augmented by a dissipative effect. Dissipation of energy is expressed as a function of the coefficient of restitution. These models are applicable for contact-impact events, and are unable to determine contact area and distribution of contact forces over it, during rolling.

In this work, the contact nodes and corresponding contact points on the surface of the elliptical disc are detected dynamically for every instant of time. The center of curvature of each contact point on the disc is determined.

The unit vector along normal to each contact point will be directed towards the center of curvature. The normal and tangential unit vectors at each contact point are obtained. The contact interface between the disc and the soft material is considered to be viscoelastic. It is modeled using virtual linear stiffness and dissipation in a parallel configuration, inserted between the disc and the soft material at the contact point, in normal as well as tangential directions. The stiffness–dissipation effect can be considered as a spring–damper subsystem. The approach allows interpenetration, and the stiffness produces restoring force proportional to the depth of penetration. The stiffness is taken to be high and can be adjusted to prevent interpenetration in the rigid body. To avoid oscillatory contact, the dissipation is tuned accordingly.

The model does not take adhesive forces into account. As the mating surfaces start separating, corresponding spring–damper subsystems get deactivated. Friction at the rigid body and the soft material contact interface is different from rigid to rigid contact interface. There occurs small displacement at the contact interface during stiction. This had been considered in 1968, by Dahl [16] where he described small relative presliding displacement between two surfaces in contact. Force resisting the relative motion of the two surfaces was considered to be proportional to relative displacement. Stiction was modeled using a stiff spring and dissipative elements, considering small presliding displacement [16–18]. In this work, the force produced by the spring–damper subsystem in tangential direction, at each instant, is compared with the limit of static friction. If it is within the limit, the friction force will be equal to the force produced by the spring–damper subsystem, otherwise sliding starts, and dynamic friction acts at the contact interface.

Cause and effect based representation of the bonds in the multibond graph facilitates better understanding of contact interaction, and derivation of system equations in an algorithmic manner. The advantages of the bond graph modeling approach have already been described explicitly in [7,8]. In this work, multibond graph model of the soft contact determines the number of contact nodes, the contact force distribution over the contact nodes and deformation of the soft material at any time. The contact area is directly proportional to the number of contact nodes; hence the model facilitates the determination of the contact area and distribution of forces for both resting contact and when bodies are in relative motion. Once the bond graph structure for the system is developed, MATLAB code is generated directly from the bond graph model in an algorithmic manner.

In this paper, bond graph model for rigid body dynamics, the soft material, and the contact interface is developed in Section 2. Detection of contact points and determination of normal and tangent unit vectors at these points on the disc surface are discussed in Section 3. Forces at the contact nodes are determined, and governing equations for the soft contact dynamics are derived in Section 4. The soft material deformation, the disc motion, change in contact area and force distribution are simulated. The simulation results are presented in Section 5 followed by conclusion at the end.

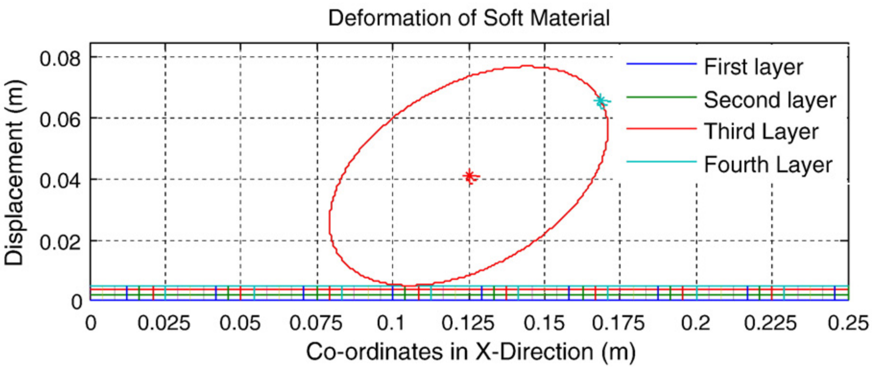

Fig. 1. The elliptical disc in inclined position contacts the soft material.