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Node-to-node scheme for three-dimensional contact mechanics using polyhedral type variable-node elements

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Abstract

A node-to-node contact scheme, which is applicable for three-dimensional contact analyses involving large deformations, is developed with the aid of polyhedral elements. The key issue is to transform nonmatching meshes into matching meshes in a seamless manner. Because polyhedral elements are allowed to have arbitrary numbers of polygonal faces and nodes, they can be used as transition elements for coupling nonmatching meshes. In this paper, the polyhedral elements make it possible to always maintain node-to-node contact during the contact deformation. The present approach guarantees that the patch test is passed and the nonpenetration condition is satisfied, and hence it yields smoother contact pressure with faster convergence than the conventional node-to-surface or surface-to-surface contact scheme.

Keywords: Contact analysis; Polyhedral variable-node elements; Large deformation; Node-to-node contact scheme

1. Introduction

The engineering approaches to contact mechanics may be categorized into two groups: the Lagrange multiplier methods and penalty methods [1]. In the classical Lagrange multiplier methods, nonpenetration condition is exactly fulfilled. However, a system matrix does not meet positive definiteness and additional variables are introduced. In contrast, the penalty method does not need any additional variables and positive definiteness of the system matrix is retained. However, the constraint conditions are satisfied only approximately according to the size of the penalty parameter, while a large penalty parameter impairs the condition number of a system matrix [2]. As a compromise between these two schemes, Arrow and Solow [3] suggested Augmented Lagrangian method. The augmented Lagrange method to treat frictional contact problems has been proposed by Simo and Laursen [4]. Furthermore, Mijar and Arora [5,6] applied the augmented Lagrange method for contact problems involving large sliding and nonlinear

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materials behaviors. Many studies on the augmented Lagrangian method show that it leads to accurate solutions just with a modest increase of computation compared with the penalty method. Thus it has established itself as one of the major methodologies for treating the contact condition in contact mechanics.

Another important issue in contact mechanics is how to handle nonconforming or nonmatching discretization, resulting from slip along contact interfaces during contact deformation. A straightforward approach to dealing with the occurrence of nonmatching meshes in contact mechanics is to transform the nonmatching meshes to matching meshes, and a remeshing scheme is employed for this [7–9]. However, this leads to a drastic increase in computing load due to the continuous remeshing and the subsequent recovery of the state variables when it comes to the cases wherein the interface configuration continues to change as in fluid–solid interaction (FSI) problems and in contact mechanics. Among others, the so-called variable-node element (VNE) approach [10–15] was suggested to overcome this shortcoming. In this approach, nodes are added on any appropriate points on each edge of a two-dimensional element or on any suitable place on each face of a three-dimensional element to transform a nonmatching mesh to a matching mesh [10–12]. Furthermore, the VNE was extended for application to FSI problems [13,14], and the smoothed finite element method (SFEM) was applied for elastic–plastic analysis [15]. Particularly polyhedral elements lead to useful three-dimensional variable-node elements [16,17], adapting themselves to complex geometries as they are allowed to have generic element shape of an arbitrary number of faces.

According to the mesh configuration on contact surface, conventional contact approaches are categorized into node-to-node, node-to-surface and surface-to-surface contact schemes. The node-to-node contact scheme, which was suggested by Francavilla and Zienkiewicz [18], is applicable in the case of conforming or matching meshes across contact interface. The advantage of this method is that the contact patch test is passed accurately, and so uniform contact pressure is exactly transferred across the contact interface. However, this approach is not applicable without remeshing if contact deformations are not small as finite tangential slip generates nonconforming or nonmatching mesh across contact interfaces.

Among well-accepted contact approaches the node-to-surface scheme is a general scheme suggested by Hughes et al. [19] To remedy its shortcoming that it does not pass the contact patch test and requires a large number of equilibrium iterations for nonconforming meshes [1,20], Crisfield [21] suggested a contact formulation by combining linear shape functions with quadratic shape functions. In addition, some work has been reported to make the node-to-surface approach pass the patch test by employing virtual slave nodes by Zavarise and De Lorenzis [22]. Many studies [23–26] have attempted to resolve this issue with the aid of various schemes such as master/slave strategy and two-layer approaches. The contact domain method [27,28] guarantees that the patch test is passed and is rather stable.

Another widely used approach is the surface-to-surface scheme, proposed by Simo et al. [29]. The surface-to-surface approach meanwhile provides solutions with high accuracy and guarantees that the patch test is passed. The mortar method, the basic concept of which originates from domain decomposition for nonconforming mesh [30], is representative of the surface-to-surface scheme. The scheme was first applied by Belgacem et al. [31] for frictionless multibody contact. In the mortar methods [32–34], traction continuity across the contact interface is enforced in the weak form with the aid of a Lagrange multiplier. This makes the system matrix positive definite, but the constraint is enforced in the sense of the weak form, and thus needed is the satisfaction of *inf–sup* condition, i.e. Babuska–Brezzi condition [34,35]. Presently, the mortar method is widely employed for diverse contact analyses [33,36–43]. Rebel et al. [44] introduced a virtual medium in contact interface using Lagrange multipliers.

A typical method for dealing with nonmatching contact interfaces is Nitsche discretization [45,46]. Contact analyses using Nitsche discretization pass the patch test and they are capable of accommodating large deformations. However, implementation of these methods is very complicated, especially in three-dimensional problems [47].

To deal with nonmatching contact surfaces in an efficient manner, Kim et al. [48] proposed a node-to-node contact strategy that can directly transform nonmatching meshes, caused by slip during the contact of dissimilar bodies, into matching meshes by inserting new additional nodes to elements along the contact interfaces. At the contact interface, all elements possessing the additional nodes are replaced by variable-node elements (VNEs) [10–12]. This novel scheme leads to fast convergence in equilibrium iterations compared with the conventional node-to-surface contact scheme. Kim et al. [48] treated only linear elastic contact mechanics within the realm of the two-dimensional infinitesimal elastic deformations. Recently, this approach has been extended to two-dimensional contact problems involving elastic–plastic large deformations [49]. The present paper is concerned with the further extension of this approach to three-dimensional contact problems with possibly large elastic deformations. The node-to-node scheme for the two-dimensional contact problems in the previous study [49] is extended to the case of the three-