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A multi-shell cover algorithm for contact detection in the three dimensional discontinuous deformation analysis

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ABSTRACT

In three dimensional discontinuous deformation analysis (3D DDA), the contact detection between blocks is the most expensive part in terms of the total computational cost. The detection normally comprises two stages, namely the search of neighboring blocks and the identification of contact modes. The first stage aims to find out all possible neighboring blocks and the second is to identify the exact contact modes between of neighboring blocks from their vertices, edges and faces. In this paper, an efficient and robust spatial contact detection algorithm is presented linking the above mentioned two stages using a novel multi-shell cover (MSC) system and decomposition of geometrical sub-units. The present MSC method greatly reduces the contact detection volume and iterations. This paper also provides a unified formula of vertex to face and edge to edge contacts. The proposed method is implemented in a 3D DDA computer program. Numerical examples are tested and the results show improved computational efficiency comparing with existing methods.

1. Introduction

The numerical methods for rock mechanics achieved great developments in the past three decades as they provide complementary guidance and predictive information that cannot be achieved by the traditional empirical ways. The most widely used continuum approaches at present are the finite element method (FEM), the finite difference method (FDM), and the boundary element method (BEM). They continue to be the mainstream in the numerical analysis of substantial rock engineering problems. However, they are faced with difficulties in dealing with problems with numerous moving boundaries, because the mesh has to be updated to conform to the evolving geometry at each time step [12]. To remove this difficulty, a variety of innovative numerical methods have been developed including the meshless methods [28–35] and the extended finite element methods [36,37], etc. However, these methods are mainly designed for dealing with material failure process. For the modeling of discrete block systems where the kinematics and removability of the blocks are concerned, the discontinuous deformation analysis (DDA) based on explicit dynamics is more suitable [1].

DDA is a discontinuum-based numerical method for blocky systems with large displacements [1,2]. Shi developed 2D and 3D DDA methods for dynamic discontinuous simulation [3–5]. The key of large displacement simulation in DDA is the contact theory including neighbor searching, contact pattern detection and contact force calculation. Contact detection process is to find candidate neighboring blocks and identify contact groups of vertices, edges and facets (geometrical elements) in a multi-block system. Contact relations between discontinuous objects are complicated both in geometry and algebra, especially for 3D cases. It requires high computational cost in contact detection of large scale problem. DDA can be classified as a type of Discrete Element Method (DEM). For 3D particle geometries, contact detection of DEM can take up to 80% of the total analysis time [19]. Thus, the computational speed and stability of 3D DDA are strongly dependent on the efficiency and robustness of contact searching and definition algorithm, which affects the simultaneous equilibrium equations solved in each step of open–close iteration (OCI) [21]. It should be also mentioned that the generation of blocks in the preprossessing can also be time consuming. The computational cost of model setup and geometry operation for numerical methods in terms of accuracy and adaptability with respect to input data has already attracted much attention. Recently, there are intense research interests focusing on incorporating the geometry and field interpolation with by the same splines, which is known as isogeometric

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analysis [38]. In comparison, the generation of blocks in DDA is lacking studies in model generation [39–45].

In contact detection, the initial contact types between blocks (vertex-to-vertex, vertex-to-edge, vertex-to-face, edge-to-edge, edge-to-face and face-to-face) are determined and translated to sub-contact types (vertex-to-face and edge-to-edge) [6,7]. Contact springs are added according to geometry and state (open, sliding or locked), contact forces and status are calculated in a series of open-close iterations (OCI).

Neighbor searching is the first step in contact detection. Apparently, a search algorithm over the whole domain is inefficient and unnecessary. In neighbor searching, algorithms for reducing search domain are used to find neighboring discontinuous blocks. Indeed, neighbor searching is an indispensable process not only for DDA and DEM but also for molecular dynamics and other discontinues methods. This is due to that fact that an automatic search technique is necessary for large-scale large displacement simulation.

Various efforts have been devoted to the development of efficient neighbor search method. Greengard [8] made extensive uses of a body-based cell approach in conjunction with octrees. They applied this method in molecular dynamics analysis. Williams [9] presented an algorithm for contact resolution with spatial heapsort and applied it to 2D DEM simulation. Munjiza [10] provided a spatial hashing algorithm based on no binary search (NBS) and tested it with large-scale discrete element simulations of bodies of similar size. Perkins [11] developed a spatial sorting based neighbor search algorithm named double-ended spatial sorting (DESS). The DESS algorithm reduces the effects of variation in size by using a spatial sorting technique applied to both ends of the object's projection along each orthogonal axis.

Contact pattern identification is the second step in contact detection. After neighbor searching calculation, specific contact pattern and contact position between two contacting blocks are ascertained. The common plane (CP) method and the geometric analysis are the two classical approaches for contact pattern identification [22,26].

Common plane (CP) method is a widely used contact pattern identification algorithm used in the DEM proposed by Cundall [14]. A common-plane bisects the space between a pair of contacting polyhedra. Both polyhedra will intersect the CP if they are in contact to each other and vice versa. Various methods have been proposed based on CP algorithms. An algorithm known as GJK, developed by Gilbert, Johnson and Keerthi, was used to compute the Euclidean distance between a pair of objects represented by convex polyhedron in three dimensional space [17]. Ong improved GJK algorithm in speed with the additional structural information on the objects. They modified GJK to apply it on objects containing complex vertices or faces [17]. Mirtich [18] provided a collision detection algorithm named Voronoi-clip for polyhedra objects specified by a boundary representation. V-clip tracks the closest pair of features between convex polyhedra in impulse-based simulation in which all contact interactions between bodies are affected through collisions. Nezami [19] introduced an efficient algorithm named the fast common plane (FCP) method to find the common plane between two polyhedrons. Properties of the CP are utilized to limit its position and reduce iterations. On this basis, also the shortest link method (SLM) was developed by Nezami to obtain the shortest link and the CP in a more efficient way [20]. Nezami pointed that the perpendicular bisector plane (PBP) of the shortest link between two particles is the CP. One disadvantage of the CP method is the limitation of convex blocks only. In case of concave blocks, error detection will occur. This reduces the usefulness of the method for substantial rock analysis since it is not appropriate to assume all blocks are concave.

On the other hand, developing algorithms calculating contact patterns among blocks directly based on their geometrical characteristics is supposed to be another way to solve the disadvantage of CP method [22]. In geometric algorithms, a polyhedron is discretized into geometric elements including vertexes, edges and facets. The 3D contact detection of polyhedral blocks includes vertex-to-vertex, vertex-to-edge, vertex-to-face, edge-to-edge, edge-to-face and face-to-face contacts [21]. Intuitively, all other contact patterns, such as vertex-to-vertex, vertex-to-edge, face-to-face, edge-to-face and edge-to-edge, respectively, can be converted into vertex-to-face contacts [15]. Wu [13], Jiang [6,23] and Liu [24] proposed a vertex-to-face contact algorithm based on geometric analysis for 3D DDA. Keneti and Jafari [25] developed a new contact detection algorithm considering main planes and dominant contacts to identify contact points and types. Beyabanaki and Mikola [16] offered an approach to identify the contact pattern between two blocks using a closest point searching algorithm as well as other 3D contact algorithms for improved efficiency [27].

The above studies mainly focus on the algorithms to select contact candidate blocks and contact patterns precisely and efficiently. After contact detection, initial contact states are set by adding penalty springs and/or frictional force [21]. Then open–close iteration (OCI) process in which an open or closed state of contact is to determine the contact states of the detected contacts in the system.

Fig. 1 shows the flowchart of a DDA code, including a geometry analysis algorithm.

As shown in Fig. 1, neighbor searching and contact pattern identification are collectively referred as contact detection which is a key process in the DDA formulation. In rock engineering, such as the cross section of a tunnel or side slopes may contain thousands or more rock blocks that govern the overall stability of rock mass. In 3D DDA, computational cost increases exponentially with respect to the number of block quantity. And most of the computational time is spent in neighbor searching and contact pattern identification.

There are two types geometrical searching loops in contact detection, namely neighbor searching loops between blocks and geometrical loops between geometrical elements. In searching loops between blocks, distances calculation of block centroids and boundaries are repeated in every time step. However, in the loops between vertices, edges and faces of blocks, contact relation judgment is complex and time-consuming. Apart from distance judgment, three dimensional projections, entry face searching and invasion judgment may occur in contact pattern identification process. Thus the contact pattern identification costs more CPU time than those in block neighbor searching generally.

In presently available algorithms, neighbor searching and contact pattern identification are the two independent stages in computations. A neighboring block pair should be detected first, and then followed by the identification of contact patterns between geometrical elements (vertices, edges and faces) of the two blocks. Due to the complexity of contact pattern identification, the more geometrical elements included in a neighboring, the higher is the computing cost.

Therefore, to reduce the unnecessary neighbor searching loops and narrow the search domain of geometrical loops will greatly improve the computational efficiency in contact detection. In this paper, a new spatial contact detection method bridging between the neighbor searching and contact pattern identification using a multi-shell cover system is presented. The multi-sphere cover system is a series of cubes or spheres used for neighbor searching. Instead of using a single circumscribed sphere or cubic shell to reduce the volume of contact detection shell, the present multi-sphere divides geometrical elements into several groups. In other words, each shell in this system is linked to a subgroup of the vertices, edges and facets of a single block. In this way, the quantity