Proceedings of the 6th International Conference on
Computation of Shell and Spatial Structures
IASS-IACM 2008: "Spanning Nano to Mega"
28-31 May 2008, Cornell University, Ithaca, NY, USA
John F. ABEL and J. Robert COOKE (eds.)

Motion Analysis of Mixed Polyhedral and Ellipsoidal Particles

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Abstract

In this paper, a new algorithm and a computer code are developed for the motion analysis of a system composed of mixed polyhedral and ellipsoidal particles. In this algorithm, we categorize the complicated contact behavior into three types as (1) ellipsoid to the ellipsoid, (2) ellipsoid to Polyhedron, (3) polyhedron to polyhedron. In addition, the contact analysis algorithm is constituted by several kinds of detail classification to accelerate the speed of simulation. The mass moment of inertia tensor of a polyhedron is calculated by a simplex integration technique. The ellipsoid is approximated by a revolution of a four-arc ellipse. The normal and shear contact forces among particles are calculated through contact spring models. Before conducting analysis of systems containing many particles, the accuracy of this code is verified by some standard testing problem of rigid body dynamics. Some packing configurations and motion analyses of mixed particles generated by this code are demonstrated.

1. Introduction

The number of processes involving solids in the chemical, petrochemical, pharmaceutical, biochemical, food industry, civil engineering as well as in energy conversion and environmental processes is such that a high percentage of the research activity is concerned with motion analysis of solids. The motion of discrete solids presents different characteristics depending on the type of system, solid concentration, arrangement, shape, cohesion and interactions. Although large sets of experimental data were available today on diverse granular and multi-phase flows, a proper discussion and understanding of the involved phenomena cannot be attained without the help of numerical simulations (Di Renzo et al. [1]). A typical technique for the numerical simulation of granular medium is the distinct element method (DEM) (Cundall and Strack [2]). The basic idea behind the DEM is based on the law of mechanics: the trajectory of each particle is calculated, considering all the forces acting on it and integrating the Newton's second law, the Euler's equation of motion and the kinematic equations for position and orientation. DEM has been applied widely in simulating and predicting the performances of many processes involving granular solids. In the analysis of DEM, the contact detection and the calculation of interaction forces among particles are the core processes. The nature of these interactions is determined by particle size, shape, density, friction angle, cohesion and other properties. These tasks will be complicated by the consideration of the nonlinear material properties and the nonspherical geometrical shapes of particles in the granular assemblies.

Few literatures can be found on the motion analysis of three-dimensional nonspherical particles using DEM. In the past decade, some researchers have used ellipsoidal solids in DEM computations (Lin and Ng [3, 4], Quadfel and Rothenburg [5]). Several investigators have developed other 3D composite nonspherical particles that are entirely composed of overlapping spheres or spherical pieces (Favier et al. [6, 7]), but these multisphere composites are neither smooth nor convex. An ovoid shape was first developed by the first author of the present paper (Wang et al. [8]) and a general ovoid shape for both oblate and prolate particles was introduced by Kuhn [9] later. On the motion analysis of polyhedral particles, Cundall [10, 11] proposed a common plane method (CPM) and implemented in the DEM program 3DEC for the system composed of many polyhedral blocks. Nezami et al [12, 13] proposed an improved version of CPM called fast common plane method (FCP) and the shortest link method (SLM) to reduce the searching time of common plane. Zhao et al. [14] developed a three-dimensional discrete element code (BLOKS3D) for efficient simulation of polyhedral particles of any size.

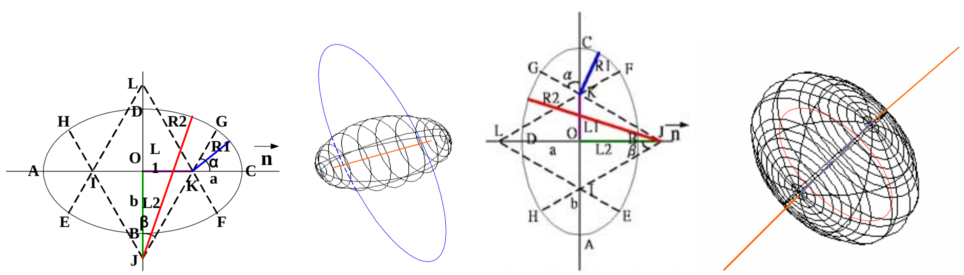
In the present paper, we focus on the problem of the contact detection of assemblies composed of mixed ellipsoidal and polyhedral particles.

2. Calculations of Particle Properties and Contact Detection Algorithms

To develop a discrete element code, the calculation of particle properties as the mass and mass moment of inertia and the contact detection algorithms among particles are the main part of the analysis. In the following sections, these subjects for the system composed of mixed ellipsoidal and polyhedral particles will be roughly explained.

2.1 Motion Analysis of Ellipsoidal Particles

To simplify the contact detection analysis of two ellipsoids in space, Wang et al. [8] have first developede a algorithm of contact detection for prolate and oblate particles generated by the revolution of 4-arc ellipses as shown in Fig. 1. Spherical surfaces are formed by the revolution of arcs FG, HE in Fig. 1(a) and by the arcs EF, GH in Fig. 1(c). Torus surfaces are formed by the revolution of arcs HG, EF in Fig. 1(a) and by the arcs FG, HE in Fig. 1(c). In this algorithm, the contact type of sphere-to-sphere, torus-to-torus and sphere-to-torus have to be examed. Detail contact theories and the calculation of the volume and moments of inertias of this kind of 3D particles can be found in the work done by Kuhn [9]. Contact force is calculated by the multiplication of the penetration depth and the contact spring stiffness. A code has been developed by the authors to conduct the motion analysis of ellipsoidal particles in space.



(a) (b) (c) (d)

Figure 1: Prolate ovoid and oblate ovoid formed by the revolution of 4-arc ellipses

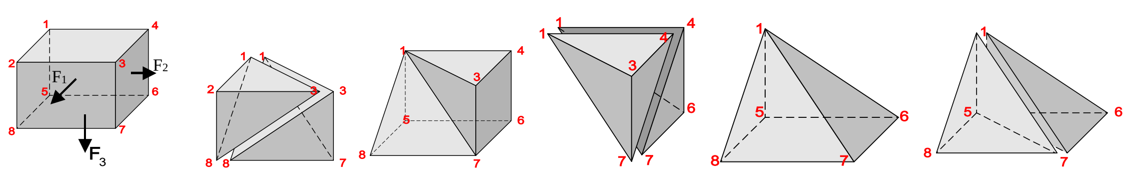
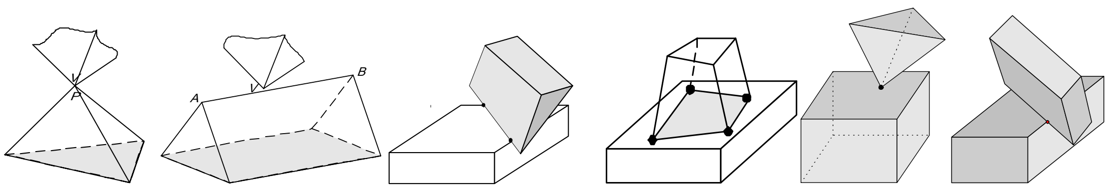


Figure 2: Decomposition of a cube into a less number of tetrahedrons by a cutting process by linking vertex 1 with triangles on face F_1, F_2 and F_3.

2.2 Motion Analysis of Polyhedral Blocks

An algorithm and a computer code have been developed by the authors (Sheng et al. [15]) developed for numerical simulations of a system composed of polyhedron of any shape, which can undergo arbitrary large motions and rotations. A cutting process was developed to decompose any polyhedron into a less number of tetrahedrons. As shown in Fig. 2, a cube is decomposed by the vertex 1 and triangles on faces F_1, F_2 and F_3; those are not in the same plane with vertex 1. The volume and the tensor of the mass moment of inertia of each tetrahedron respect to the global coordinates can be calculated by the simplex integration developed by Shi [16]. Then the parallel theorem is used to determine the tensor of the mass moment of inertia of the polyhedron respect to its centroid. In the motion analysis of polyhedral blocks, only contact types of vertex-to-face and edge-to-edge are required for contact detection, although six types of contacts are possible between any two polyhedral blocks as shown in Fig. 3. It is noted that, the vertex-to-face contact and the edge-to-edge contact are the fundamental modes of the other four contact types. In addition, the contact system is decomposed into contact detection hierarchies to accelerate the simulation speed. The mutual reactions among elements are taken account by the relative forces and contact through normal and tangential spring model.

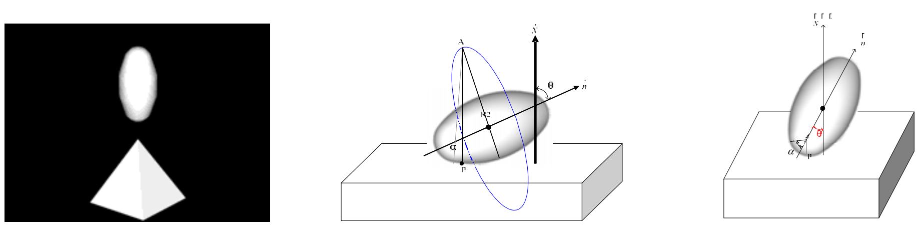


(a) (b) (c) (d) (e) (f)

Figure 3: (a) vertex-to-vertex contact, (b) vertex-to-edge contact, (c) edge-to-face contact, (d) face-to-face contact (e) vertex-to- face contact, (f) edge-to-edge contact.

2.3 Motion Analysis of Mixed Ellipsoidal and Polyhedral Particles

In the motion analysis of a particle assemblies composed of ellipsoids and polyhedrons, the contact analysis between ellipsoid and polyhedron is another task. There are three contact types: vertex-to-ellipsoid contact, edge-to-ellipsoid and face-to-ellipsoid between these two kinds of particles. The detections of the first two types of contact are standard features of coding. While the contact between an ellipsoid and a face of polyhedron is further evaluated by which section of the ovoid contacts the polyhedral face. As shown in Fig. 4 (b), if the angle θ between the revolution axis $\vec{n}$ and the normal vector $\vec{N}$ of the face is larger than the half range angle α of spherical section, the torus section of the ovoid may contact the polyhedral face. Furthermore, If the extreme distance between the point A on an outer ring of the torus section and the point P on face is less than the radius r_2 of the torus surface, then the point P is the contact point of the torus section of the ovoid with the polyhedron. If the angle θ is less than the angle α , then the spherical section of the avoid may contact the polyhedral face. It contacts the face when the distance between the centroid and the face is less than the radius r_1 of the spherical section. Figure 5 shows the motion analysis of mixed ellipsoidal and polyhedral particles conducted by the code developed based on the aforementioned theories.



(a) (b) (c)

Figure 4: (a) vertex-to- ellipsoid contact, (b) contact between torus section of an ovoid and plane, (c) contact between spherical section of an ovoid and plane.

(a) (b) (c) (d) (e)

Figure 5: Motion analysis of mixed ellipsoidal and polyhedral particles.

3. Discussion and Conclusions

The distinct element method (DEM) has proven to be effective in characterizing the behavior of particles in granular flow simulation. This paper presents a simulation algorithm for the motion analysis of medium composed of mixed ellipsoidal and polyhedron particles. It describes an effort to enhance the available algorithms and further the engineering application of DEM. Contact detection of the complex geometrical configuration at any time is the main part of the presented paper. However, the modeling of the collision process between particles is critical to the accuracy of simulation. It should be well investigated in the future.

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