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Rotation and Reshaping of Self-gravitating Aggregates

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Abstract

Using a Soft-Sphere DEM code we simulate the reshaping and disruption of a self-gravitating 3D granular aggregate by increasing its spin rate. During the process, we monitor the evolution of the internal stresses in the aggregate to find its yield stress using the Maximum Stress, Von Mises and Drucker-Prager yield criteria. In the simulations we either increase the number of particles or their density to increase the total mass of the aggregate and find an increment in the yield stress. In addition, once a reshaping spin rate (density dependent) has been reached, its further increase causes further reshape (ultimately fission) and a decrease in the spin rate itself.

1. Introduction

Given the current understanding that asteroids can be in fact rubble-piles held together by gravitational and cohesive forces, it is necessary to understand their internal mechanics if we are to understand how they have evolved to show the variety of sizes, shapes and configurations that we can attest today. One of the possible reasons for these varied features could be the rotation and subsequent fission of the primary asteroid. The research presented here investigates the reshaping process and the internal stress that the primary undergoes as a result of secular increases in angular momentum and before fission occurs.

2 Simulations and Yield Criteria

In our studies we simulate the particles forming the asteroid by means of a Soft-Sphere Discrete Element Method code [1, 2]. This simulation method allows sustained multi-particle contacts. Contact forces, including static and dynamic friction, and gravitational forces are calculated.

The self-gravitating aggregates are initially formed without friction to obtain a maximum, controllable, packing fraction. Spherical aggregates are obtained by initially encapsulating the aggregate inside a sphere of a known size, whereas ellipsoidal shapes are reached through an initial angular velocity. In the simulations, the formed asteroid is divided in regular cubes containing tens of particles and the average stress tensor in each on of them is calculated as:

$$\bar{\sigma} = \frac{w}{V} \sum_{c \in K_V} \vec{f} \otimes \vec{l} \qquad (1)$$

where V is the volume in which the calculation is taking place, K_V is the set of contacts between the particles in the volume V, $\vec{f}$ is the reaction force due to a contact and $\vec{l}$ is the relative position of one particle with respect to the other (branch vector). The eigenvalues of the stress tensor of the particles in each volume define the stress state of its particles and of the aggregate as a whole.

We use the Maximum Principal Stress Theory (MS), von Mises (VM) and Drucker-Prager (DP) yield criteria to analyse the internal stress field. This provides a value for the yield stress σ_y and an angle of repose.

3 Results and Observations

Our results show that self-gravitating granular aggregates do reshape slowly, leading eventually to material shedding only when there is no friction, regardless of the initial shape (fig. 1-2nd column). Initially spherical frictional aggregates disrupt by shedding material from the equator; however their prolate counterparts combine disruption by shedding and eventually disrupt by fission (see fig. 1-3rd column).

The inclusion of friction in the simulation produced a very visible change in the dynamics of the systems. As pointed out by Holsapple [3], after the first reshaping event, it is impossible to make the aggregates rotate at a higher angular velocity. This was found to be true only for frictional aggregates and not for their frictionless counterparts.

We have also observed that perfectly spherical aggregates are more likely to acquire and retain an oblate

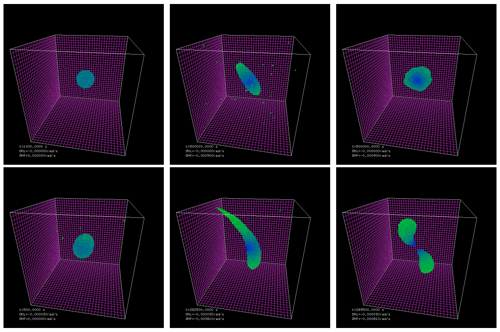

Figure 1: Simulations: reshaping and disruption. 1st row: initial shape, final shape without friction, final shape with friction. 2nd row: initial shape, disruption process without friction, disruption process with friction.

shape when friction is present. In addition, even though deformation induced a decrease in the packing fraction of the aggregates (down to ≈ 0.6), this dilation was only maintained when friction was present in the simulation. Frictionless aggregates always reacquired their original filling fractions of ≈ 0.65.

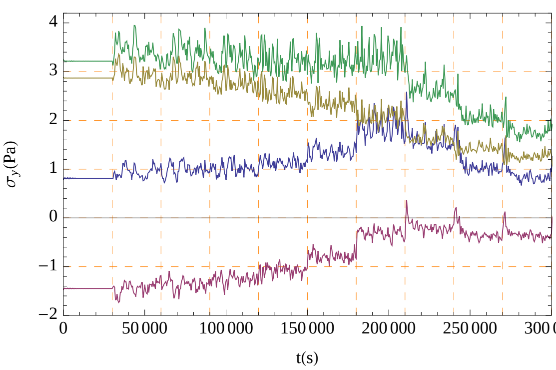

Figure 2: Time evolution of the stress criteria: frictional-spherical aggregate. MS is dark green, VM is blue and DP is red. The light green line just under the MS line represents the maximum value of the hydrostatic pressure.

The values found for the yield stress given by the VM criterion and the angles of repose obtained trough the DP criterion confirm that, even with the same density and number of particles, spherical aggregates (2.40 Pa and 31°) are structurally stronger than ellipsoidal ones (2.1 Pa and 23°). Frictionless aggregates show an angle of repose that is only a few degrees greater for spherical aggregates (13.6°>12°) and have the same value for yield stress. The values of ω_c were found to depend on the bulk density of the aggregate [4]. Frictionless aggregates started to reshape at the same angular velocity regardless of their initial shape. However, frictional aggregates, maintaining the same dependency, show higher values of ω_c so reinforcing the idea of greater structural strength.

As for the internal stresses, the maximum stress is usually near the centre of the aggregate; hydrostatic pressure increases with the total mass of the aggregate and decreases with increased spin rate. From the yield criteria used, it seems that the Drucker-Prager yield criteria is the simplest to use as the only requirement for reshaping is that its value is greater than zero (see fig. 2). It is also the one that provides more information, as by adjusting the height of the peaks to be greater than zero when reshaping is apparent, it is possible to find an effective angle of repose.

4. Summary and Conclusions

In this abstract we present the results of the simulation of self-gravitating granular aggregates that undergo a reshaping and fission process due to the increase in angular velocity. We find that the frictional and frictionless aggregates show different reshaping and disruption processes, ω_c depends on the bulk density of the aggregate, and its initial shape. After ω_c has been reached, a further increase in spin rate only causes more reshaping and decrease in the spin rate due to the increase in moments of inertia.

Acknowledgements

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