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Characterization of force networks in a dense high-shear system

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ABSTRACT

We detect strong force networks in a dense high-shear system and study their structure and stability in response to variations in the shearing rate. The presence of strong force networks, which usually have a heterogeneous structure, restricts particle movements and can impose non-local mechanisms of momentum transfer. We identify such networks in a dense high-shear system using a community detection algorithm. Moreover, we explain the association between the mechanisms of momentum transfer and the structure, population, strength, and stability of the force networks by tracking the spatial and temporal evolution of the detected networks. In addition, we show that the assumption of a monodisperse assembly of particles leads to an unrealistic enlargement of the force networks, underestimating both the rate of energy dissipation and the rate of mixing.

Introduction

In the process of particle mixing, and especially in high-shear granulation, strong force networks are undesirable as they restrict the movement of the particles and reduce the rate of mixing. A force network is considered to be a group of particles connected to each other through a network structure in which the force is anisotropically distributed through particle–particle contacts (Radjai, Wolf, Jean, & Moreau, 1998). Such network structures behave similarly to a rigid body in the way that they transfer the force from one boundary to another without major internal deformation. Clearly, these heterogeneous arrangements and the resulting non-local mechanisms of momentum transfer cannot be dealt with under the assumption of isotropic solid pressure, as required by local rheology models. Consequently, the identification and quantification of the properties of force networks are necessary to determine their effects on the behavior of particle systems.

Generally, a force network is considered to be strong if the averaged normal force between its members is larger than the system's average normal force (Radjai et al., 1998). Such structures avoid the dissipation of energy through particle–particle interactions. Thus, in a dynamic system, the energy preserved within the structures of the force networks would lead to faster particle movements along the direction of the driving stresses (Donev, Torquato, & Stillinger, 2005; Gao, Fan, Subramaniam, Fox, & Hoffman, 2006). For the reasons given above, it is unsurprising that force networks in dense particle assemblies have received considerable interest in the literature (Majumdar & Behringer, 2005; Mueth, Jaeger, & Nagel, 1998; Radjai, Jean, Moreau, & Roux, 1996). One example is the influence of polydispersity on the structure of force networks. According to Gao et al. (2006) and Radjai et al. (1996), polydispersity breaks the homogeneous ordering of the particles that gives rise to strong force networks and induces non-local mechanisms of momentum transfer (Gao et al., 2006).

The force networks can have different shapes and structures. A specific class of force networks comes in the form of linear or quasilinear strings of rigid particles, often termed "force chains". The characterization of force chains has been the subject of many studies, and a variety of methods have been proposed in this regard. For example, Peters, Muthuswamy, Wibowo, and Tordesillas (2005) identified the force chains as particles in a quasilinear arrangement containing a concentrated stress. Other studies have considered force chains in terms of their stability (Campbell, 2003), structure (Van Siclen, 2004), and size distribution (Mueth et al., 1998; Radjai et al., 1996).

Despite the studies mentioned above, there is no unified quantitative measure for characterizing force networks. A number of criteria have been proposed to detect force networks in granular assemblies (Bouchaud, Claudin, Levine, & Otto, 2001; Campbell, 2003; Cates, Wittmer, Bouchaud, & Claudin, 1998; Peters et al., 2005; Sun, Jin, Wang, & Zhang, 2010; Van Siclen, 2004): concentrated compressive stresses (Van Siclen, 2004), linear strings of at least three rigid particles (Cates et al., 1998; Cates, Wittmer, Bouchaud, & Claudin, 1999), and quasilinear particle networks

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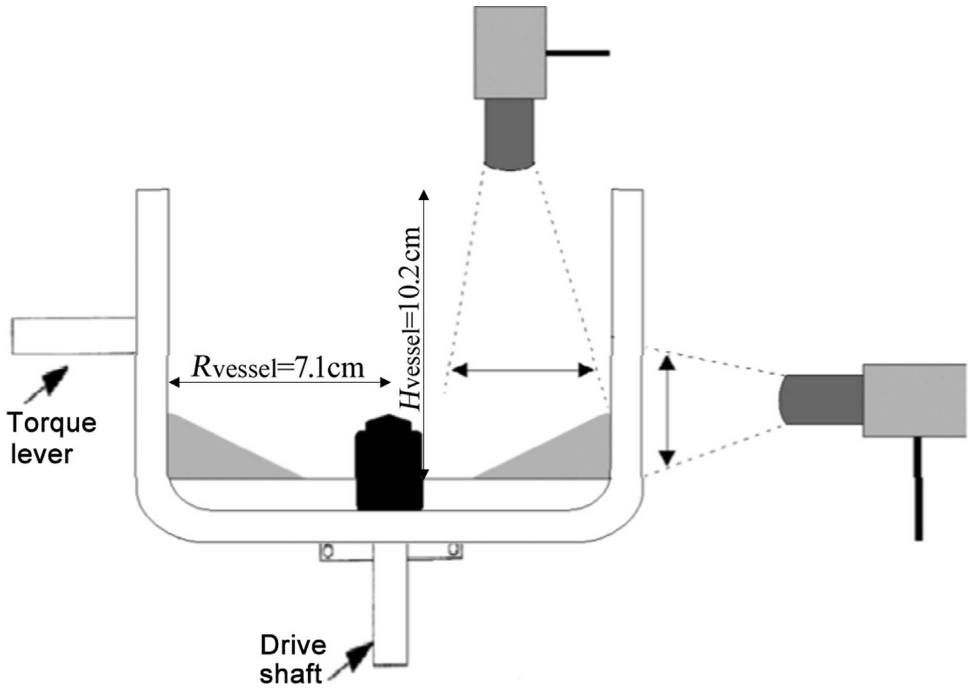

Fig. 1. Experimental setup used in this study. Note that the imaging is performed separately, once through the sidewalls of the equipment and once from the top. Thus, the two cameras in this image do not imply synchronized 3D imaging. It should also be noted that, as the bump in the middle of the setup does not affect the flow of the particles, it has not been included in the simulations.

(Campbell, 2003; Luding, 1997; Peters et al., 2005). However, the majority of these methods are either limited to the detection of force chains (linear or quasilinear force networks) and no other network architectures (Peters et al., 2005; Silbert, Grest, & Landry, 2002), or are only applicable within static and two-dimensional (2D) systems (Zhou, Yu, Stewart, & Bridgwater, 2004; Zhu, Zhou, Yang, & Yu, 2008). In contrast, methods based on network science have shown strong potential to identify and characterize such structures quantitatively within complex configurations of dynamical particulate systems (Bassett, Owens, Porter, Manning, & Daniels, 2015). These methods automatically identify the force networks in a particle assembly using community detection algorithms (Fortunato, 2010; Liu, Pellegrini, & Wang, 2014; Porter, Onnela, & Mucha, 2009).

The aim of this study is to find an association between the structure and strength of force networks and the mechanisms of stress transmission. We consider not only the force chains, but also force networks in general, regardless of their geometry. Additionally, this study aims to explain the variations in the dynamic behavior of a disk impeller high-shear granulator at various impeller speeds by characterizing the structure and lifecycle of the force networks. We look at the strength, lifetime, and density map of the force networks and evaluate the influence of polydispersity and impeller rotational speed on those quantities.

Experimental

The experimental setup is a disk impeller granulator, which is a cylindrical vessel (diameter = 14.2 cm) with a rotating bottom plate. The setup is similar to the equipment used by Gantt and Gatzke (2006) and Reynolds, Nilpawar, Salman, and Hounslow (2008). The equipment is loaded with 225 g of spherical glass beads (uniform distribution, 1.3 ± 0.01 mm in diameter). The equipment was operated at four different impeller speeds (200, 800, 1500, and 3500 rpm) and the flow field was measured for each case using high-speed imaging and particle image velocimetry (PIV) from two different angles (sidewalls and top view). A multi-pass method (Raffel, Willert, Wereley, & Kompenhans, 2007) with window sizes from 32×32 to 64×64 pixels was used to give a suitable number of particles for averaging in each interrogation window (10–40 particles per interrogation window). Considering the high quality of the images and the fact that the profiles were averaged over 500 frames (set of velocity vectors), the error can only arise from the calculation of the pixel-to-length translation factor. As a result, we estimate the error to be of the order of 0.1 mm/s, which is a maximum of 0.05% compared to the velocity magnitudes. In addition, the torque exerted on the wall boundaries was measured in each experimental case. The experimental setup is schematically represented in Fig. 1.

The maximum torque was observed at an intermediate impeller speed (800 rpm). Similarly, the tangential velocity of the particles attained a maximum at 800 rpm, with any further increase in impeller speed causing the particles to move slower and the torque to decrease. Further details about the experimental methodology have been reported by Khalilitehrani, Abrahamsson, and Rasmuson (2013).

Measurements using PIV show the aforementioned non-monotonic trend in the velocity field (Fig. 2(a)) versus the impeller speed, and torque measurements show a similar trend for the total torque exerted by the rotor (Fig. 2(b)).

Method

Discrete element modeling

The discrete element method (DEM) is a numerical modeling technique that considers the forces exerted on every individual particle and the contacts between the particles and boundaries to model the behavior of the system. The method integrates the forces acting on every individual particle at every time step, and applies Newton's second law of motion to calculate their translational and rotational motions (Eqs. (1) and (2)). These forces typically include gravity, the influence of the surrounding fluid (if any), contact forces with the neighboring particles, and so on.