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ACCEPTED MANUSCRIPT

Grain- and Macro-scale Kinematics for Granular Micromechanics based Small Deformation Micromorphic Continuum Model

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Research highlights

- Granular micromechanics paradigm with enriched kinematic description proposed.
- Identification of macro- with grain-scale kinematic variables developed.
- Micro- and macro deformation energies shown to yield novel stress-force relations.
- Pathway to non-classical micromorphic model with grain-scale representation shown.

Abstract

Macro-scale deformation of granular solids comprising large number of grains ($>10^6$) are most efficiently described within the framework of continuum mechanics. It is notable, however that the micro-scale deformations in these materials are concentrated at the grain-boundaries or grain-contacts. Thus, the deformation energies in these systems must be modeled by considering the deformations concentrated in the neighborhood of the grain-boundaries or grain-contacts. To address this issue, grain-interactions has been widely described in the Hertzian sense by considering the relative movement of points on either side of a grain boundary or contact treated as an imperfect interface. This communication introduces the relevant kinematic variables given in the terms of the grain displacements, spins and size that can be used to estimate the relative movement of a grain boundary or contact. The macro-scale kinematic variables useful for continuum modelling are then identified with the grain-scale kinematic variables. The deformation energy density of the granular solid can thus be expressed both in terms of the grain-scale as well as the macro-scale kinematic variables providing the necessary pathway for micro-macro identification which can lead to non-classical micromorphic continuum models that incorporate grain-scale representation.

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Keywords: granular micromechanics; micromorphic continuum; grain spins; stress-force relationships; moment stress; double stress.

1. Introduction

Continuum modeling continues to be attractive and, arguably, the most feasible approach for describing the mechanical response of granular solids at macro-scale. It is notable, however, that in granular materials, the micro-scale deformations are concentrated in the close neighborhood of the grain-boundaries or grain-contacts. Therefore, for granular material systems, the grain-pair interactions and granular structures have a strong effect upon the collective behavior of grains. The imperatives of including the grain-scale information in the macro-scale continuum models of granular solids have been widely recognized (see among a subset of early authors [1-8] and more recent contributions [9-12]). Clearly, the deformation energies of these material systems must be modeled by considering the deformations concentrated in the neighborhood of the grain-boundaries or grain-contacts. To address this issue, grain-pair interactions are often treated as two solid bodies with an imperfect interface and the relative movement of the grain centroids are identified with the relative movements of points on either side of the interface, such as that exemplified by the contact theory of solid bodies [13] or mechanics of interfaces of crystals [14].

This communication focusses upon discussion of the kinematic variables necessary for determination of the grain-pair relative movement and their relationships to continuum counterparts. To this end we introduce two new grain-scale kinematic measures, defined in the terms of the grain centroid displacement, spin and size; one for determining relative displacements and the other for relative rotations. These

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