Dynamic characterization of micro-particle systems

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Abstract

Ordered granular systems have been a subject of active research for decades, due to their rich dynamic response and nonlinearity. For example, their extraordinary wave propagation properties, shock absorption ability, and tunability are of interest for different scientific communities that range from condensed matter physics to applied mathematics to engineering. Thanks to their unique nonlinear properties, ordered granular systems have been suggested for several applications, such as solitary wave focusing, acoustic signals manipulation, and vibration absorption. Most of the fundamental research performed on ordered granular systems has focused on macro-scale examples. However, most engineering applications require these systems to operate at much smaller scales (for example, to affect acoustic signals in the ultrasound regime within acoustic imaging applications). Very little is known about the response of micro-scale granular systems, primarily because of the difficulties in realizing reliable and quantitative experiments. These experimental difficulties originate from the discrete nature of granular materials and their highly nonlinear inter-particle contact forces. The discreteness and accompanying micro-scale sizes require efficient means to assemble the particles precisely, to excite them, and to measure their dynamic response. The high nonlinearity in these systems requires particularly high precision, and imperfections can be extremely important in controlling the dynamic response of the entire system.

In order to characterize micro-scale, ordered, granular systems, it is necessary to understand the fundamental physical mechanisms that govern their response. For example, do the same physical laws that govern the macro-scale granular response apply? Does the Hertzian elastic contact theory hold? What is the role of the particle/substrate interactions? How does stress propagate through micro-scale particle systems and what are the main defects that affect these systems?

In this work, we address these questions by designing an innovative experimental platform that allows us to assemble, excite, and characterize ordered micro-granular systems. This new experimental platform employs a laser system to deliver impulses with controlled momentum and incorporates non-contact measurement apparatuses (including high-speed optical microscopy and laser interferometry) to detect the particles' displacement and velocity. We first built and programed a computer-controlled micro-manipulator that can position and assemble steel micro-particles in

configurations that are desired for testing. We then fabricated microstructures to guide and confine the micro-particle assembly. Next we tested and demonstrated the capability of the laser excitation system to deliver controlled momentums to systems of dry (stainless steel particles of radius 150 μm) and wet (SiO_2 particles of radius 3.69 μm, immersed in fluid) micro-particles, after which we analyzed the stress propagation through these systems.

To describe the fundamental dynamic mechanisms governing the response of dry and wet micro-particle systems, we derived the equations of motion governing the dynamic response of dry and wet particles on a substrate, which we then validated in experiments. We then measured the losses in these systems and characterized the collision and friction between two micro-particles. We next assembled one-dimensional dry chains of micro-particles and investigated the mechanical wave propagation properties as well as the influence of defects in these systems. We also studied wave propagation in two-dimensional colloidal systems immersed in fluid. Finally, we experimentally characterized the wave-attenuation and its relation to the viscosity of the surrounding fluid and performed computer simulations to establish a model that captures the observed response.

The findings of the study offer the first systematic experimental and numerical analysis of wave propagation through ordered systems of micro-particles. The experimental system designed in this work provides the necessary tools for further fundamental studies of wave propagation in both granular and colloidal systems. The findings also offer fundamental insights for the miniaturization of highly nonlinear granular devices.

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