Chapter 7

Conclusion & Future Work

7.1. Conclusion

In this thesis, we design an innovative experimental platform that allows us to assemble, excite, and characterize ordered micro-granular systems. In Chapter 2 and 3, we detail the design of a new experimental platform that employs both a laser system to deliver impulses with controlled momentum and non-contact measurements (including high-speed optical microscopy and laser interferometry) to detect particle displacement and velocity. We fabricate micro-structures to guide and confine the one-dimensional micro-granular system that is assembled using a computer-controlled micro-manipulator. In addition, we employ self-assembling techniques to create two-dimensional hexagonal lattices in micro-fluidic cells. We test and demonstrate the capability of the laser excitation system to deliver controlled momenta to the above 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.

In Chapter 4, we study the dynamics of particles in a one-dimensional micro-structure support. We first derive the governing equations of motion that describe the dynamic response of dry and wet particles on a substrate. To investigate how a micro-structure support influences the dynamics of micro-particles that are loaded onto it, we study the loss in our micro-particle configuration both analytically and experimentally. We measure the Stokes' and Coulomb friction of the micro-particles by tracking their trajectories at varying initial momenta. We study the collisions of rolling micro-particles in a groove to investigate the exchange of translational and angular momenta during collisions. Through observing inelastic collisions of rolling particles and nearly elastic collisions of particles that are initially in contact, we discover a linear dependency between the contact force and the tangential frictional force between the colliding particles. We obtain empirical equations of motions that describes the dynamics of the micro-granular system.

In Chapter 5, we investigate the mechanical wave propagation properties as well as the influence of defects in one-dimensional, dry chains of micro-particles. We measure the attenuation of the mechanical wave along the chain at different initial striker velocities and show that it agrees with the theoretical prediction. We measure the delay time of wave propagation inside the chain and show that measured group velocity depends on the initial velocity. We compare the deviation of the measured group velocity with the case of a Hertzian system, and we numerically show that the deviation can result from the presence of defects (which here are gaps between micro-particles). To prove this we use the microscopic system to perform time of fly measurements for systems with a known maximum gap. We show that the measured group velocity agrees the numerical simulation.

In Chapter 6, we study wave propagation in two-dimensional colloidal systems that are immersed in fluid. We produce controlled mechanical wave impulses within the system, study the total energy transfer at varying laser energy, and observe the system's response displacement. We experimentally characterize the wave-attenuation and its relation to the viscosity of the surrounding fluid and perform computer simulations to establish a model that captures the observed response.

In this thesis we describe the first systematic experimental and numerical analysis of wave propagation in ordered systems of micro-particles. This work provides a foundation for advancing fundamental research of granular and colloidal systems and offers basic insights into the miniaturization of applications based on highly nonlinear granular systems.

7.2. Future work

In this thesis we present a new experimental framework and study micro-granular systems constructed on supporting structures that are fabricated with photolithography technology. Modern micro-fabrication technology provides us with well-studied fabrication processes that enable more sophisticated micro-structures for constructing micro-granular systems. The fabrication technology provides great experimental freedom for future studies related to micro-granular systems with different geometries, improving micro-granular system assembling, and the mechanical response of a hybrid system of a micro-granular and elastic materials.

The local, instantaneous delivery of momentum to micro-particles that is used in these experiments have several advantages. In the wet particle experiments, we demonstrate that with the high initial velocity that is generated by laser ablation, the particles have enough energy to overcome the hydrodynamic boundary and to interact with other particles with contact force (which is a regime that is difficult to access using traditional experimental tools for colloidal dynamics). This allows us to explore experimentally the interplay between hydrodynamic interaction and contact interaction, and influence of these interactions on the collective behavior of the lattice. Using chemical growing techniques, colloidal particles can be fabricated to carry desired softness, surface roughness, and attractive or repulsive inter-particle electrostatic forces. The laser-based excitation system can be used to examine the dynamics of the customized fabricated colloidal systems.

This flexibility of laser excitation can also be applied to one- or three-dimensional colloidal systems. Since the laser only interacts with non-transparent particles that are near its focal point, a laser excitation can be delivered to the target particles within three-dimensional systems with negligible influence on other particles. This provides us with new ways to excite mechanical waves at specific locations within the colloidal systems, which will be useful for researching new categories of mechanical waves (which are difficult to generate using traditional means).

Non-contact laser-based excitation has a great advantage over traditional contact-based excitation, which is the ease of producing excitation at multiple locations by splitting and redirecting the laser beam. While we only use the laser to excite a single particle within the system in this study, the capability of exciting the system at multiple locations allows us to investigate the interaction between mechanical waves that are generated at different locations within the granular system. Future studies of the collision and interference of mechanical waves within micro-granular systems can advance the fundamentally understanding of the micro-granular system as a medium of wave propagation.

The mechanical response of the laser ablation has significant space for improvement. The stainless steel particles used in this work were not chosen for their good material response, and the complicated material composition of stainless steel is a possible cause of the 15% variation on output velocities. Future systematic searches for a better ablation material for mechanical wave generation would benefit the accuracy and repeatability of these laser-based experiments. An ideal ablation should possess efficient material response, high repeatability, low material consumption per ablation, and little influence on the sample. While materials with these properties might not be available, we expect that a great improvement in ablation performance could be achieved through switching to material that is better than stainless steel. Our experimental capacity would benefit from a material that is ideally suitable for mechanical wave generation, as it would enable accurate, repeatable, continuous operation of mechanical wave generation.

Finally, other than the material response of the laser ablation, more work can be done to improve particle manipulation mechanisms via the sophisticated control of laser beam profiles and positions.

Modern optics have a variety of tools to shape the laser pulse in time and spatial domains. For example, a spatial light modulator can alter the beam profile and direction by modulating the phase of the laser profile using liquid crystals. This device can be used to create multiple focus points as well as to shift the focus point in real time. Together with the image acquisition and processing system, future work to explore the manipulation of non-transparent colloids in micro-fluid systems with an optical griper that consists of laser focal points would benefit our fundamental ability to manipulate micro-particles. This advance could in turn be applied to studying complex two- and three-dimensional structures in colloidal systems or to manipulating objects in bio-mechanical systems. Unlike the optical tweezer (which can only be applied to transparent targets), laser ablation can be applied to non-transparent targets; as a result it can provide control over entirely different categories of micro-objects.

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