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 programmed 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\textsubscript{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.
Table of Contents

Acknowledgements ........................................................................................................ iii
Abstract ............................................................................................................................ iv
Table of Contents .............................................................................................................. vi
List of Figures ................................................................................................................... viii
List of Tables ..................................................................................................................... xiii
Introduction ...................................................................................................................... 5
  1.1. Motivation and significance .............................................................................. 5
  1.2. Background concerning granular materials ..................................................... 7
    1.2.1. Ordered granular systems ......................................................................... 7
    1.2.2. Micro-scale granular systems ................................................................. 11
  1.3. Contributions of this thesis ............................................................................. 12
  1.4. Conceptual organization of this thesis ............................................................... 14
Instrumentation ................................................................................................................ 15
  2.1. Particle confinement and sample stage ............................................................ 17
    2.1.1. One-dimensional micro-granular systems ............................................. 17
    2.1.2. Two-dimensional micro-colloidal systems ........................................... 21
  2.2. Laser power controlling and beam conditioning .............................................. 22
  2.3. Measurement system ........................................................................................ 24
    2.3.1. Laser vibrometry .................................................................................... 24
    2.3.2. High-speed micro-photography .............................................................. 27
  2.4. Configuration of the laser focusing system ....................................................... 30
    2.4.1. One-dimensional micro-granular systems ............................................. 30
    2.4.2. Two-dimensional colloidal hexagonal lattices ....................................... 30
  2.5. Software system and lattice construction ......................................................... 31
Mechanical Excitation via Pulsed Laser Ablation ......................................................... 34
  3.1. Theory of laser ablation for nanosecond lasers ................................................. 35
  3.2. Pulsed laser ablation on stainless steel micro-particles .................................... 37
    3.2.1. Accuracy and repeatability ..................................................................... 39
  3.3. Pulsed laser ablation on silicon dioxide colloids ............................................. 41
  3.4. Summary ........................................................................................................... 43
Micro-particles in One-dimensional Confinement ......................................................... 45
  4.1. Modeling the motion of a sphere in a groove ..................................................... 46
  4.2. Motion of one micro-particle in a groove ......................................................... 48
  4.3. Modeling the collision of two particles in a groove ........................................ 51
  4.4. Collisions between two particles in a groove .................................................. 55
  4.5. Summary ........................................................................................................... 59
The Dynamics of Dry, Microscopic Granular Chains ..................................................... 60
  5.1. Modeling solitary waves in micro-granular chains ......................................... 60
  5.2. Wave propagation in micro-granular chains ..................................................... 63
  5.3. Gaps in micro-granular chains ....................................................................... 66
5.4. Summary ........................................................................................................... 69
Wave Propagation in a Two-dimensional Colloidal System ............................ 70
6.1. Modeling the two-dimensional colloidal systems............................... 71
6.2. Excitation of mechanical waves in colloidal systems......................... 73
6.3. Mechanical wave propagation in colloidal systems ......................... 77
6.4. Summary ........................................................................................................... 82
Conclusion & Future Work ............................................................................. 84
7.1. Conclusion ..................................................................................................... 84
7.2. Future work .................................................................................................. 85
Bibliography ....................................................................................................... 88
List of Figures

Figure 2.1: Overview of the experiment scheme. The apparatus consists of three major parts, including the excitation system (focused laser pulse), the measurement system (high-speed microphotography and laser vibrometry), and the sample assembly and manipulating system. .................................................................16

Figure 2.2: An SEM image of micro-particles used in this experiment. (a) Stainless steel 316 particle with a radius of 150 µm and surface roughness of 3 µm. (b) Stainless steel 440c particle with a radius of 150 µm and surface roughness of 0.1 µm. ..........................................................18

Figure 2.3: Micro-fabrication process of one-dimensional v-shaped grooves with a width of 240 µm and an inclined angle of 70.6º. (a) Overview of the fabrication process: i) Chemical vapor deposition of a 1µm thick layer of silicon nitride (Si3N4) on the surface of a 1mm thick silicon wafer [100]. ii) Spin coating with 1.6 µm of AZ5214 positive photo-resist. iii) Exposing and developing the photo-resist. iv) Patterning the silicon nitride layer with reactive-ion etching (RIE). v) Anisotropic chemical etching with a 50% potassium hydroxide (KOH) solution at 85ºC. (b) An SEM image of the resultant v-shaped grooves. .................................................19

Figure 2.4: Procedures for assembling a micro-granular chain. (a) i) Micro-particles are positioned loosely in a v-shaped groove. ii) The sample stage is tilted to create a close-packed granular chain, blocked at one end by a robotic tip. iii) The sample stage is tilted back horizontally and the tip is withdrawn. (b) Optical imaging system to determine the locations of the particles using an image-processing algorithm. The image of the particle in the red box is used as the kernel of the image deconvolution, to reveal the position of other particles. The blue curves below show the results of the deconvolution algorithm, through which the other four particles are detected. A particle’s position can be obtained with 2µm accuracy. .........................................21

Figure 2.5: Preparation of two-dimensional micro-colloidal systems of SiO2 particles. Hexagonal lattices are created by self-assembling techniques. (a) The micro-fluid cell used in this experiment. (b) A schematic diagram of the cell tilting process. (c) A digital image of dense, disordered micro-particles in the cell at the beginning of the relaxation process. (d) The final hexagonal lattice with a coated particle in the center .................................................................22

Figure 2.6: (a) Photograph of a laser vibrometer shining on the surface of particles with a radius of 150µm; the beam waist of the vibrometer beam is 3µm. (b) Schematic diagram of a realistic use case of a vibrometer being used on micro-particles. The red line indicates the beam of vibrometer, while d is the offset of the beam to the center of the particle and θ is the angle between the particle displacement, x, and the laser beam. .................................................................24

Figure 2.7: Calibration of vibrometer output. (a) Calibrations are performed by focusing a laser beam on the surface of a micro-particle and then using the computer-controlled sample stage to move it along its expected direction of motion in experiments (i.e., along the axis of the v-shaped groove). (a) The measured displacement (red dots) compared with the displacement of the sample stage (and the particle). The slope of the (blue) fitting line shows that there is a factor of 1.24 between the output velocities of the vibrometer and the real velocities in the horizontal plane. ........................................................................26

Figure 2.8: Schematic diagram of the experimental setup. (a) Two laser vibrometers are pointed on the micro-granular chain that is constructed with the procedures shown in Fig. 2.4. The granular chain consists of 15 particles and the vibrometers are pointed at the 2nd and 13th
particles. (b) Calibration of vibrometer output. Two vibrometers are focused on the same particle. To calibrate vibrometer measurements, we point two vibrometers on the same particles and measure the relative time delay in output signals. ...............................................................26

Figure 2.9: Image processing of the high-speed image sequence of a micro-particle moving on a groove. (a) Image of a micro-particle in a microstructure with an exposure time of 990 µs. (b) Image of the same particle with an exposure time of 39µs. (c) A portion of (b) is manually selected for use as the kernel of the deconvolution algorithm. (d) Resultant trajectory of the micro-particle moving under the camera. ........................................................................................................28

Figure 2.10: A typical high-speed image of the wet two-dimensional micro-granular system and the results of image processing. (a) Image of a micro-particle in a microstructure with an exposure time of 2.7 µs. (b) Resolved positions of colloids with image processing algorithm. The blue circles are the initial positions at t=0, while the red circles are the positions after 3.3 µs. .......29

Figure 2.11: Experiment configuration for one-dimension micro-granular systems. (a) Micro-particles loaded on the supporting structure are assembled to the desired configuration by the computer-controlled micro-manipulator. The samples are monitored with a high-speed imaging system above the sample holder and a vibrometer that is pointed at the surface of a micro-particle. The focused laser beam with 15 µm is aligned to shine at the outer-most surface of the particle to excite the sample. (b) One-dimension micro-granular chain assembled in a v-shaped groove. ........................................................................................................30

Figure 2.12: Experiment configuration for colloidal systems. (a) SiO2 particles are injected into micro-fluid cells made of transparent material, in which self-assembled hexagonal lattices are created. The laser beam is merged with the illumination and focused at the same focal plane of the high-speed imaging system. The laser is targeted at the coated SiO2 particles at the center of the lattice. The resultant response is measured by the high-speed imaging system above the sample. (b) Hexagonal lattice of SiO2 micro-colloids. ........................................................................................................31

Figure 2.13: An example of the procedure for positioning and assembling micro-particles. (a-d) Schematic of four basic manipulations of a micro-particle, including pushing the particles to the left (right) and gently touching the particle from the top to open up gaps. (e) Procedures of relocating micro-particles to the two targeted positions that are marked by the red crosses, i-iii) open a small gap between the two particles in contact by lightly brushing on one of the particles from the top; iv-v) after enough space is available, separate the two particles; vi-viii) push the micro-particles to the target position. .................................................................................................33

Figure 3.1: High-speed images of a micro-particle (114 µm radius, stainless steel 440c) on a v-shaped groove being illuminated by a pulsed laser at t=0 ms. Ejected materials can be seen at t=0 ms and the damage on the particle’s surface can be seen at t=1 ms and 9 ms. The sequential reappearance of the damaged surface indicates that the particle is rolling after being excited. ..................................................................................................................37

Figure 3.2: (a) Experimental scheme of calibrating the dependency of the transferred momentum to the laser pulse energy. (b) Momentum obtained by particles of two different materials (stainless steel 316 and 440c) at different laser inputs. ................................................................................................................38

Figure 3.3: Repeatability of the laser ablation method to excite particles on a substrate. (a,b) Experimental diagrams. (a,c) Schematic diagram and results of the experiment measuring the angular dependency of the momentum to the off axis distance. (b,d) Schematic diagram and results of the experiment measuring the accuracy requirement for particles along the optical axis of the laser. A 15% variation of output velocity is observed. ..................................................................................40

Figure 3.4: Excitation of micro-colloids’ motion in water. We focus the laser on the micro-colloids in liquid. (a) The target particle (marked with a white arrow) before the laser is shone on it. (b) During the laser excitation, the laser radiation can be seen at the original position of the target particle. (c) The target particle is relocated to a new position (again marked with a white
Figure 4.1: A particle in a v-shaped groove. The direction in which the particle is moving is defined as the z-direction. The particle is supported by the groove’s two inclined surfaces. In comparison to when particles are placed on a flat surface, the geometry of the v-groove enhances the frictional force by a factor of $1/\sin(\theta/2)$, where $\theta$ is the angle between the two surfaces of the v-groove. For the particles to roll without sliding on the groove, the groove’s translational and angular velocities need to satisfy $\nu z = R\omega x$.  

Figure 4.2: Experimental investigation of single micro-particles moving in a groove. (a) Schematic diagram of the experimental setup: a laser (green beam in the diagram) excites a particle in a groove, with a controlled pulse energy. We tested two types of micro-particles, stainless steel 316 and 440c. (b) A typical measured trajectory of an excited micro-particle. The transition from a rolling and sliding motion to rolling without sliding can be found by using an optimization algorithm to obtain the empirical parameters $T$ and $\mu pg$, as a function of initial velocity. (c) $T$ is found to depend linearly on the initial velocity $T' = 0.052 + 1.10v_0$. (d) Stainless steel 316 particles have a mean of $\mu pg = 0.337$ (dashed line) and stainless steel 440c particles have a mean of $\mu pg = 0.296$ (dotted line) for $v_0 > 0.03$ m/s. The error bars are plotted with $\pm \sigma/2$, where $\sigma$ is the standard deviation of the measurement. 

Figure 4.3: Experiments involving particle collisions in a groove. (a) Experimental schematics. Two cases of collisions are tested: a particle collides with another particle that is i) separated by 1 mm, or ii) in direct contact with it. (b) Digital image of the particles during the experiments. The blue and red dashed boxes identify the striker and the target particles, respectively. (c) Trajectories of the two colliding particles. (d) Rolling and sliding motion and rolling without sliding motion as identified for the striker particle. This trajectory reveals information on the angular motion of the particle. 

Figure 4.4: Experimental results for the collisions of two particles. (a) A linear correlation between the change of translational and angular velocities during collisions of two 440c particles is observed. The error bars are plotted with $\pm \sigma/2$, where $\sigma$ is the standard deviation of the measurement. Fitting shows the normal force and tangential force can be described with Coulomb friction with a frictional constant of 1.4 (b) The coefficient of restitution between two stainless steel 316 particles when they are rolling (red squares) or initially in contact (orange triangles). (c) The coefficient of restitution between two stainless steel 440c particles when they are rolling (blue circles) or initially in contact (purple diamonds). 

Figure 5.1: Numerically computed nonlinear waves traveling in an uncompressed, micro-granular chain that consists of 15 stainless steel particles (440c) with a radius of 150 \( \mu \text{m} \). The first particle (the striker) has an initial velocity of 0.1 m/s. (a) Velocities of micro-particles along the chain. The solitary wave is seen to evolve to a stable shape after traveling through the first few particles. (b) Calculated maximum particle velocity at different initial striker velocities. The results can be fitted with a linear relation, $v_{max} - 0.64v_s$. (c) Calculated group velocities (red dots) at different initial striker velocities. The results match with the analytical solution for a granular chain (Eq. (1.4)) if the $v_{max} - 0.64v_s$ obtained in (c) is assumed. 

Figure 5.2: Measured particle velocities in a micro-granular chain of 15 stainless steel 440c particles (a) Measured particle velocities (rescaled with the calibration Eq. 2.1 and normalized by the striker velocities) for the 2nd and 13th particles in the chain. From these data we obtain the maximum particle velocities, $v_{max}$, and the time delay $\Delta t$. (b) Measured maximum velocities (red dots) of the two monitored particles. The red fitting line has a slope of $0.80 \pm 0.08$ (95% confidence interval). (c) Measured maximum velocities (normalized to...
the striker velocity). An averaging gives \( \text{vmax}, 1/V_{\text{striker}} = 0.57 \pm 0.09 \) and \( \text{vmax}, 2/V_{\text{striker}} = 0.46 \pm 0.07 \) (95% confidence interval). (d) Measured group velocities at different striker velocities.

Figure 5.3: Wave propagation in micro-granular chains with gaps. (a) Schematic diagram of the setup obtained by assigning a random gap between neighboring particles. (b) Numerical simulations for waves propagating in a granular chain with gaps. The initial velocity is 0.1 m/s and the average gap size is 20 nm (c) Group velocity as a function of the striker velocity, at various gap sizes. Purple line: simulation of an ideal chain (gap=0). Pink bands: simulation results with randomly generated gap distributions, at a fixed average gap size ranging from 10 to 190 nm. Dashed lines: theoretical predictions obtained with Eq. (26), based on the group velocity of a close-packed chain. The measured group velocity is fitted with the simulation results (dashed lines) of systems with averaged gap = 190 and 47 nm for stainless steel 316 and 440c, respectively.

Figure 5.4: Experimental data of group velocity at different gap sizes. The chains are excited with an initial velocity of 0.01m/s and group velocities are measured on a loosely packed chain. (a) Measurement of the total length of the chain. (b) Experimental data for the group velocity (brown dots) and predictions (dashed line). The data are scattered but remain below the upper bound of the dashed line.

Figure 6.1: Images of laser excitation of micro-particles in a hexagonal lattice. (a) Photograph of a lattice prepared for laser excitation. The dark particle in the center is a micro-particle coated with 50 nm of Au that is targeted by the laser. (b) Excitation of the system with a weak laser pulse with energy of 0.1 \( \mu \)J. The target particle obtains an initial velocity in the direction of the red arrows. (c) Excitation of the system with a strong laser pulse of 0.25 \( \mu \)J. Isotropic wave propagation in all directions is observed.

Figure 6.2: The velocity and kinetic energy transfers to the colloidal system by laser excitation. The velocity map of the system excited at (a) 0.13, (b) 0.19, (c) 0.21, and (d) 0.23 \( \mu \)J shows that at lower energy (less than 0.15 \( \mu \)J in our system), the laser can only excite the linear motion of the coated particles. At higher power the laser is capable of exciting mechanical impulses in all six hexagonal directions. The higher the laser energy, the farther the wave can reach out from the center. (e) The total kinetic energy of micro-particles in the lattice at different laser powers and background fluid viscosities. The energy transfer efficiency is about 0.001%, which is close to the efficiency when exciting one particle (see Chapter 3).

Figure 6.3: Numerical study of wave propagation along a chain within the hexagonal lattice. (a) Schematic diagram of the excitation and geometry of the lattice (b) The velocities of particles along the chain. (c) The total displacement (red dots) after the excitation obtained through simulation. It is fitted with an exponential decay formula and gives the decay length of 2.7. (d) The inter-particle distance during wave propagation.

Figure 6.4: Experimental data of a wave propagation in the colloidal system with a viscosity of 0.01 Pl is excited by pulse energy of 0.16 \( \mu \)J. (a) The measured velocity map of the system. The red boxes show the geometry of chains in the six hexagonal directions from the center particle. (b) The displacement of the particles that are shown in the red boxes in (a). (c) The decay length measured at different combinations of laser energy and viscosity.

Figure 6.5: Velocity maps of the system tested at different laser energy and background fluid viscosity. The system is tested under a combination of viscosity equaling 0.001 Pl and 0.004 Pl and laser energy equaling 0.16, 0.20, and 0.25 \( \mu \)J.

Figure 6.6 Numerical simulation of wave propagation generated with different initial velocities and fluid viscosities; \( \mu \) and \( \nu \) are (a) 0.001 Pl, 8 m/s and (b) 0.004 Pl, 24 m/s. The higher initial velocity in the second case is included to account for the higher initial velocity obtained from the same laser energy acting on a system with higher viscosity.
List of Tables

Table 2.1: Dimensions and material properties of our stainless steel micro-particles [129, 130].
Particles made of stainless steel 316 and 440c are used in this work. These two particles have
similar physical properties except for the significant differences in surface roughness and
thermal conductivity........................................................................................................................................19
Table 2.2: Dimensions and material properties of the colloidal particles used in the wet, two-
dimensional experiments................................................................................................................................22
Table 6.1: The parameters for numerical simulation with Eq. (6.1). ..........................................................73