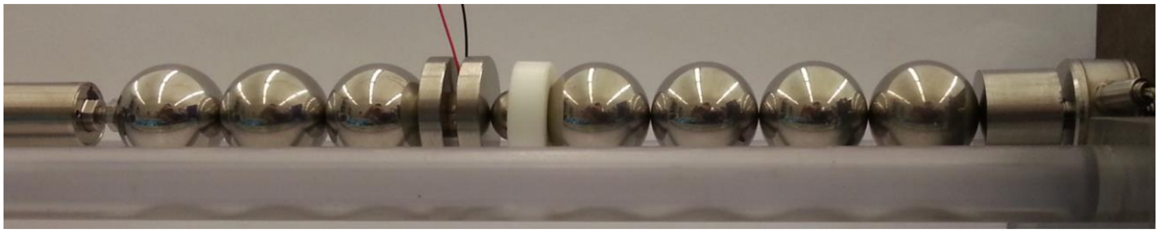
Chapter 3

EXPERIMENTAL SETUP

The majority of the experimental tests have a similar setup with different measurement and excitation techniques depending on the particular experimental goals. In this section I present the basic experimental setup, the recurring measurement techniques, and the more subtle differences required for each experiment.



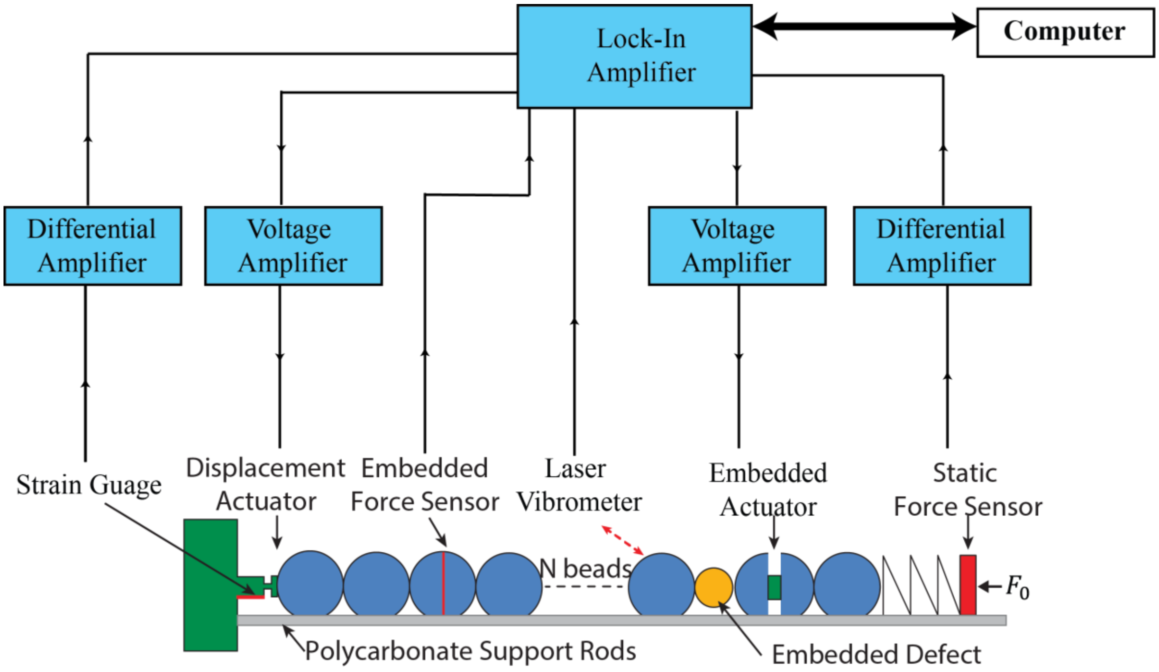


Figure 3.1: (Top) Picture of the experimental setup used in the tunable stiffness experiments (chapter 6). (Bottom) Schematic of the Experimental Setup. Each of the different parts of the experimental setup are indicated with text. We use the different input and output channels of the Lock-In amplifier to both excite and monitor the state of our system. The physical setup consists of an array of spherical particles aligned between two boundaries. In the schematic the boundary conditions are considered as fixed boundary conditions. The particles are supported by polycarbonate rods and are excited using piezoelectric actuators (green). These actuators can be both embedded in particles in the array and placed at the end of the array. Measurements are taken using either dynamic force sensors, static strain measurements, or velocities from the laser vibrometer (red). The voltage signals that need to be processed are indicated in blue. Each part of this setup is described in the following section.

3.1 General experimental setup and tools

The 1-D granular crystal is a periodic array of grains or particles[35]. In our system our repeat unit particle is a stainless steel type 316 sphere (McMaster-Carr) with a measured radius $R = 9.525\, mm$, measured mass $m = 28.84\, g$, Youngs Modulus $E = 193\, GPa$, and Poisson ratio $\nu = 0.3$.[91] These particles are aligned using two polycarbonate rods and are fixed between a piezo-electric actuator and a force sensor or soft spring which provide fixed or force controlled boundary conditions, respectively. The overall mechanical structure and support of the system is similar to previous experimental studies of granular crystals[27,31,32,68,69].

Most of the dynamics that we are interested in are either nonlinear resonances or linear resonances, and all the experimental studies include a harmonic drive source. It is therefore extremely important to be aware of the different frequency responses and resonances of the building blocks of the system, nearby noise sources, and also the measurement tools. The masses and coupling stiffness between particles leads to an acoustic band up to 7kHz when compressed at 10 N. Since our system is nonlinear the actual frequencies of interest change depending on the initial compression. I present these numbers as a baseline to keep in mind which frequency ranges we are interested in. The principal mode of vibration of a single bead will be much higher (~30kHz) than the dynamics we are interested in. This can therefore initially be ignored. In additions the steel blocks, acting as a boundary condition, and the supporting table have resonances at low frequencies, less than 1 kHz. These resonances can be ignored when studying systems at higher frequencies but must be either filtered or accounted for when the frequencies of interest are lower.

In the experiments, it is important to always consider the boundary conditions and how this may affect the involved dynamics. We have two primary methods to apply an initial compression to the granular chain. One boundary will always be a stiff wall. This could be a force sensor or a piezoelectric actuator attached to a large steel block. The important thing to consider here is that the piezoelectric actuator or force sensor is stiffer than the Herztian contact stiffness. In this configuration the boundary condition is displacement controlled. The second boundary condition that we use is a soft spring, to allow more control over the static compression of the chain. In this configuration, the soft spring should be many orders of magnitude lower than the contact stiffness, and the boundary condition is considered to be a force controlled boundary.

The choice piezo actuator has inherent tradeoffs. We utilize a variety of piezo actuators that are chosen to either excite or displace the system. The resonances of the piezo stack actuators should always be chosen so that the frequency response of the actuator is flat over the excitation range and the resonance is far above the band or spatially separated from the dynamics. This means that the larger displacement actuators (with resonances at 3-4 kHz) should only be used to compress the system when studying dynamics localized at a distance from the actuator. Smaller displacement actuators used for excitations should have resonances high above the band ($\sim 30kHz$) and be driven using amplifiers designed for high impedance capacitive loads.

We use polycarbonate rods of 6.4 mm radius to support and align the granular particles. The polymer rods have two important considerations. The first is to reduce the coupling between the stainless steel particles and the supporting structures. The choice of polymer rods instead of steel rods enhances the impedance mismatch. The second consideration is low friction. Although the particle displacements are quite small, the velocities are significant. It is therefore important to reduce frictional dissipation mechanisms that are external to the granular crystal. These may be highly variable and also difficult to predict and quantify.

3.2 Measurement tools and techniques

In the granular chain we have three different measurement tools including, static load cells, dynamic force sensors, and a laser vibrometer, to study the dynamics of the system. Each of these tools have advantages, limitations, and important considerations.

The static load cells (Transducer Techniques SLB-25 and Omega LCMFD-50N) rely on a wheatstone bridge technology. This is the circuit for a strain gauge that relies on a constant voltage source and outputs a small differential voltage in response to strain which can be translated directly to force. The voltage is amplified using a differential amplifier and then filtered using a low pass 4th order filter, in order to reduce high frequency noise. As is indicated by their name the static load cells should not be used under dynamic loading conditions. The primary function of the static load cells in the granular chain is to measure the initial static compression of the system. Due to the nonlinearity of the system, the dynamics change from weakly nonlinear to strongly nonlinear depending on which compression regime the experiments are performed. It is therefore important to monitor the static force in the granular crystal.

We use two types of dynamic force sensors. One is a commercial quartz sensor (PCB 208C01) and the second is an embedded piezoelectric disk[77]. The commercial sensor has a corresponding signal conditioner which uses a current source to amplify the signal at the source, thus minimizing noise problems. Therefore the commercial sensor is desired when possible, but due to its size we implement it only at the ends of the chain. The piezoelectric sensor is smaller and can be embedded in particles for in-situ force measurements. The disadvantage is the low voltage signal in response to strain. The voltages can be quite low and are subject to noise problems. We therefore use lock-in amplifiers and filtering techniques to gain accurate amplitude and phase information for the signal. Finally, when measuring or amplifying the piezo signal it is important to have a high input impedance compared to the relatively high impedance of the piezo. We present an extended description of the dynamics of this device in section 4.2.2.

We use a Doppler laser vibrometer (Polytec CLV-2534) to measure the velocity of the beads. The primary advantage of this technique is that it is completely non-invasive, meaning the measurement does not affect the dynamics of the granular chain. We assume that the motion of the particles is completely aligned with the chain, with no off-axis component. Using this assumption, the measured velocity is just the particles velocity projected onto the laser measurement direction. The laser can be translated to sequentially measure velocities of different particles in the chain. We use the laser vibrometer with an internal low pass filter at 100KHz and a high pass filter at 100Hz. For our experiments the laser vibrometer is used in conjunction with a lock-in amplifier, therefore measuring the steady state velocities. This provides an advantage in providing information not only about the amplitude of a harmonic signal, but also phase information. This phase information allows us to relate the steady state velocities of neighboring particles and therefore image the steady state amplitude profile (i.e., the mode profile) over the entire chain with a single measurement tool.

The measurements are digitized and subsequently analyzed using either a data acquisition board (National Instruments NI-6115) or a lock-in amplifier (Stanford Research Systems SR830 or Zürich Instruments ZI-HF2LI). The data acquisition board (DAQ) from National Instruments provides an ideal way to measure transient and non-harmonic dynamics of the system. The DAQ board measures time series of the waveform and can measure changes due to a system bifurcation and features of the waveform when it is not sinusoidal. The measurements across channels are simultaneous and each channel has its own analog to digital converter, allowing high time resolution without suffering any cross-talk between channels. In addition, the device has 12 bit resolution, allowing for better amplitude resolution than many 8 bit oscilloscopes.

The lock-in amplifier acts as a very powerful measurement tool to gaining information about a steady state response. This measures the sinusoidal characteristics of a system by computing the Fourier component at a reference frequency. The principal function is to output a amplitude and phase of a voltage signal with respect to a reference wave. This allows us to sweep over frequency or another variable of our system and watch how the system response changes. This works well to see the linear response of the chain and the nonlinear bending of modes. In addition, since we know the phase relation of neighboring particles we can plot experimentally measured modes. The downside of using a lock-in amplifier is the time needed get accurate measurements. The lock-in operates by multiplying the reference signal and measured voltage signal and low pass filtering, i.e., integrating. This prevents us from observing the transient dynamics and is therefore limited to the steady state response. In addition, it means that the total settling time is related to the time constant of the low pass filter. We must integrate long enough to allow both the system and the lock-in dynamics to settle. Typically in our measurements we use a time constant on the order of, $\tau \sim 30\ ms$, and a 4th order filter. This is sufficiently long enough to measure the steady state dynamics at $3-15\ kHz$.

3.3 Specific experimental setups

3.3.1 Local to extended transitions of resonant defect modes

For this experiment (results in chapter 5) , we introduce a resonant defect in the granular chain by attaching an external ring structure to one of the particles [49]. This structure has a mechanical resonance measured experimentally at $6.2\ kHz$. We embed this resonant defect in the center of a 31-particle chain, with 15 stainless steel spheres (type 316, 9.525 mm radius) placed on both sides of the resonant defect. This is a one-dimensional finite crystal with a defect in the center. The particles are aligned between a $90\ \mu m$ compression actuator (Physik Instrumente P-841.60) and static force sensor (Omega LCMFD-50N). A laser vibrometer (Polytec OFV-534) sequentially measures velocities of half the chain and the defect particle. Embedded force sensors are placed next to the defect and at the end of the chain. All dynamic measurements are taken at steady state using a lock-in amplifier (Zurich Instruments ZIHFLI). We drive the defect's resonating mass and measure the forces and velocities of different particles in the lattice.

During the experimental analysis, we measured the defect mode's velocity profile at each static compression and then used this profile to calculate the mode's localization. During this compression, we follow the entire mode's evolution and can observe the transition from a localized to a delocalized mode.

3.3.2 Extraordinary stiffness tunability

The experiments are carried out on a 1-D lattice of 9 spheres of 9.525 mm (results in chapter 6). We replace the central bead by a defect bead with a radius of 4.763 mm, and we replace the bead next to the defect by a piezoelectric actuator (Physik Instrumente PD050.31) held between two stainless steel cylinders with a radius of 10 mm and a length of 4 mm.

The amplitude of vibration is measured using a laser Doppler vibrometer (Polytec CLV-2534) pointing at the particle next to the defect, and the compression force is measured using a static load cell (Omega LCMFD-50N) and amplified with a gain of 100. The electrical outputs from the sensors are measured with a lock-in amplifier (Zurich Instruments ZI-HF2LI). The strain on the lattice is prescribed using a high-stroke piezoelectric actuator (Physik Instrumente P-841.60). The force-displacement curves are obtained at a steady state by waiting 1.5 seconds to ensure quasistatic behavior.

3.3.3 Nonlinear resonance in finite granular chains

We assemble a one-dimensional (1D) homogeneous granular chain made of N stainless steel spheres between an excitation actuator and a soft spring (results are in chapter 7). We excite the system with a harmonic displacement for approximately 400 ms, enough time to reach stationary dynamics, using a low voltage piezoelectric actuator (blocking force 800 N, resonance frequency 40 kHz, PST 150/5/7 VS10 provided by Piezomechanik). The actuator is mounted on a steel block fixed to the table. N spheres (with N ranging between 1 and 50) are then aligned with the head of the actuator and supported by polycarbonate rods. We excite with a range of static and dynamic loading that allows access to both the weakly and strongly nonlinear dynamical regime. We use a non-contact laser vibrometer to measure the dynamic response of the short granular systems (i.e., $N \leq 2$) at the last bead, ensuring no effects of the measurement system on the results. In longer systems, we use calibrated sensor particles, placed in the third and last bead, similar to Job et al.[78] The applied static load is measured using a calibrated static force sensor.

3.3.4 Essentially nonlinear frequency bands

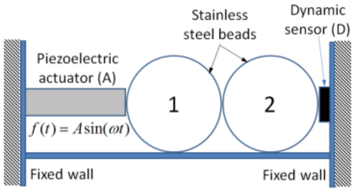


Figure 3.2: Schematic of the experimental setup used for the essentially nonlinear frequency bands, chapter 8.

In this experiment, we consider a system of two beads placed between a dynamic sensor (PCB 208C01) and a piezoelectric actuator (PST 150/5/7 VS10) [92] (Fig. 3.2). The actuator is used to harmonically excite the first bead. The dynamic force sensor measures transmitted force and is used to infer the dynamics and state of the system, i.e., whether the system is driven in a strongly or weakly nonlinear regime. We adjust the offset bias of the actuator to achieve dynamics at near zero static compression.