SURF Interim Report 1

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Motivation and background

Polycatenated architectural materials (or PAMs for short) are structures where ring-shaped units link together to create a chainmail-like mesh. The study of force and energy dispersion in such materials are not yet well studied, especially in 3D PAMs. Due to the Hertzian contacts between each ring unit, they exhibit properties unique to nonlinear dynamics not observed in linear systems, especially in the context of pulse and wave propagation. As such, they have various potential applications in effective shock absorption (such as in helmets), as well as interesting physical phenomena from a theoretical standpoint. The Daraio lab group has so far studied the way these PAMs respond to external force, and the way wave pulses travel through 1D PAMs.

This project investigates the propagation of longitudinal wave pulses in 2D PAMs and other structures such as Y-shaped junctions of 1D ringblock chains. The results can be compared with the lab group's simulation based on current theory to either validate or correct our understanding of longitudinal force distribution in 1D and 2D PAMs. In addition, this experiment can be taken further by investigating other modes of excitation within 2D PAMs, such as transverse waves and even rotation. This is possible by leveraging a key property of PAMs, where the contact between each unit allows for various modes of force transfer, in contrast to a granular model which can only transfer longitudinal "pushing" forces. The experimental study of force distribution and energy dispersion in 2D chainmail material advances our understanding of PAMs, as a key step towards learning about the properties of 3D PAMs. Understanding the physical properties of PAMs is a crucial step in potentially exploiting PAMs as useful materials and improving our understanding of more complex, nonlinear structures.

Approach

The overall setup consists of a 2D mesh of repeating ring-like units pretensioned in both dimensions, some units with sensors to detect the mechanical pulse, and an actuator that sends in the pulse.

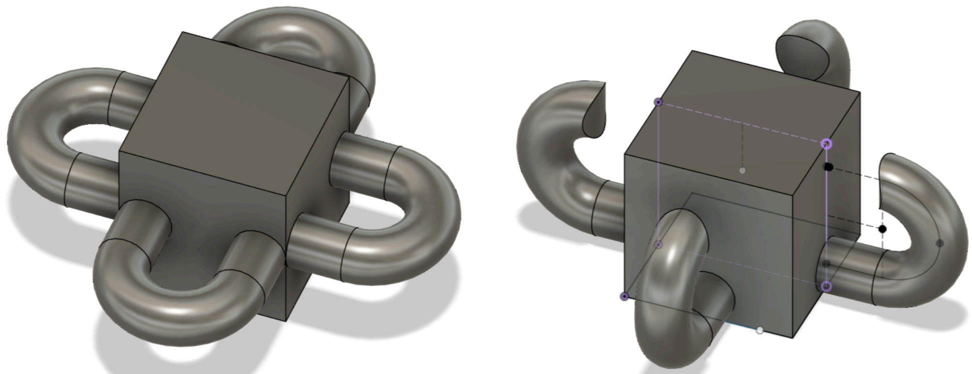


Figure 1: “Ring blocks” designed and used for this experiment, horizontal rings on the left and a vertical hook design on the right

We first modify the geometry of each unit according to Figures 1 and 2, to add more control parameters and modes. They consist of a cube with rings extending out from its four faces, and will be referred to as a “ring block”. The rings have a semicircular end extended linearly from the cube, which allows us to independently control the spacing between each unit as well as the curvature of the ring-like contact. The vertical ring block has a gap at the top, which was mainly made to ease the physical setup of the experiment and manufacturability. This way, the chain or mesh of ring blocks can be taken apart and reshaped instead of having to manufacture each set at once.

By inserting either a piezoelectric sensor or a triaxial accelerometer into one of the ring blocks, it is possible to detect longitudinal mechanical wave pulses traveling through these blocks. Placing these sensor blocks within various parts of the chain or mesh allows us to detect how much of the pulse traveled to that point (amplitude) and at what time. In tandem with other sensors in other locations, we can calculate the overall wave speed, how much the pulse was dissipated, and how the pulse propagates throughout the mesh.

To send in the wave pulse, we will use a piezoelectric actuator connected to a ring block to send a short pulling impulse. High constant voltage would be applied to the actuator such that it would be extended, then via a very short square wave, set the voltage to 0 before returning to the high voltage. The actuator would contract then extend back, sending a pulling impulse throughout. This can also be modified to send a pushing impulse, which we can also investigate.

We decided to tackle the 1D chain case using these ring blocks first, then build our way towards a 2D mesh. In this way, we can validate the ring blocks' basic behavior under a wave pulse, to make sure they behave as expected, as we improve the setup step by step. We first check with a 1D chain, then investigate a junction where multiple 1D chains from different directions are linked together. Finally, we make a 2D mesh of the ring blocks to investigate.

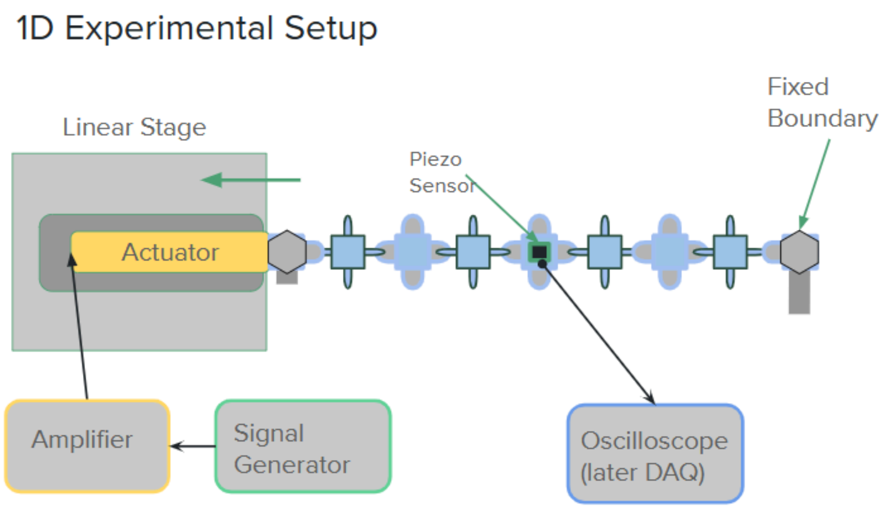
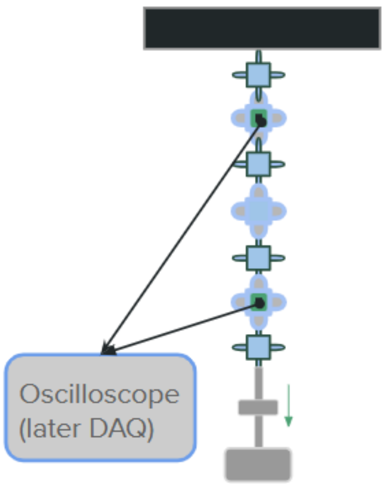


Figure 2: Setup of the 1D chain version of the experiment with implemented devices

Accomplishments

The ring blocks were designed, 3D modeled, and subsequently 3D printed using PLA. After several iterations, we landed on the design shown in Figures 1 and 2. We also created sensor blocks that incorporate piezoelectric sensors, which enabled successful detection of wave pulses as they traveled through a 1D chain of PLA ring blocks. Most significantly, looking at signals from 2 sensor blocks (one closer to the origin of the pulse than the other), we were able to identify the same initial pulses on each sensor, and obtained fairly consistent time differences in detections of the same pulse in 2 different positions on the chain ($\sim 780 \pm 20$ μs). This allowed for a calculation of the overall wave speed along this chain, which was about 10 times slower than the wave speed through solid PLA. For this check, we hung it vertically and used a falling mass to send the pulse, as done in the previous experiment.



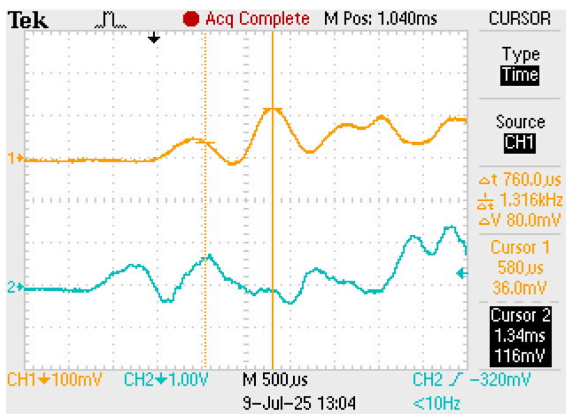


Figure 3 (left): A simplified diagram of the setup used to check how well the pulses may be detected with PLA ring blocks and piezoelectric sensors
Figure 4 (right): Sensor readings from 2 blocks, where the blue signal is from a sensor block closer to the source of the pulse than that of the orange signal.

Additionally, we were able to successfully drive and actuate the piezoelectric actuator using a signal generator and an amplifier. We are nearing completion of the setup implementing the piezoelectric actuator, using a linear stage to apply pretension on the ring blocks.

Challenges

One challenge we had was measuring the manufacturing time and cost of the ring blocks, especially with rigid material that allows mechanical pulses through well such as polycarbonate, aluminum, or steel. Certain services had a long lead time and very high cost, but we luckily found a service that 3D printed them with a reasonable time and cost. The product will ship soon, which we will test and evaluate.

A foreseeable challenge is how the mesh of ring blocks may be very unstable when suspended midair. While it is possible that the pretension is enough to maintain the blocks' overall positions, because the mesh would be suspended midair, each one could easily orient itself out of the plane, which would be unfavorable for the investigation of longitudinal wave pulses in the mesh. An option may be to place them on a flat surface, but the friction and contact between the mesh and the table may cause unwanted physical interactions. A fraction of the wave pulse could also travel into the table instead, although this may not happen if a completely horizontal actuation is provided into a horizontal ring block mesh.

A related challenge is the method we would use to consistently pretension the ring blocks, especially with the ability to measure the applied pretension. One solution is to implement a load sensor in between the linear stage and the actuator to directly measure the tension force. A possible issue with this is that the load sensor's strain may affect the actuation and weaken or disrupt the wave pulse. This solution will be tested and explored to see how small or large this effect is. Another is to use a tension load sensor on the other end to determine what displacement is necessary on the linear stage for a given tension force, then to swap the force sensor with a hard boundary and reapply the recorded displacement.