Photoelasticity Resource Sheet

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Making Photoelastic Particles/Sheets

- Materials:
  - Vishay PhotoStress Plus http://www.vishaypg.com/micro-measurements/photo-stress-plus/ comes in sheets of several different stiffnesses. A 2-part castable liquid is available as well. ($$$, 4-6 week delivery)
  - Clear urethane sheets http://www.precisionurethane.com/ are a cheaper alternative to the above, and a 2-part castable liquid is available as well (e.g Clear Flex from http://www.benam.co.uk/products/urethane/clear-flex/ or http://www.smooth-on.com/Urethane-Rubber-an/c6_1117_1153/index.html) Both forms come in a variety of stiffnesses, and can be clear or dyed. ($$)
  - Clear acrylic/Plexiglas, which is widely available but too stiff for many experiments. ($)
  - Unflavored gelatin: cast your own disposable sheets/particles. Start with a recipe somewhere between ordinary dessert and jello-shots, and adjust your ratios from there. ($)

- Particle size:
  - Particles need to be wider than they are tall so that they don't tip over when sheared.
  - Cut at least 10% more particles than you will need: particles (although athermal) nonetheless manage to diffuse out of experiments into the environment over time.

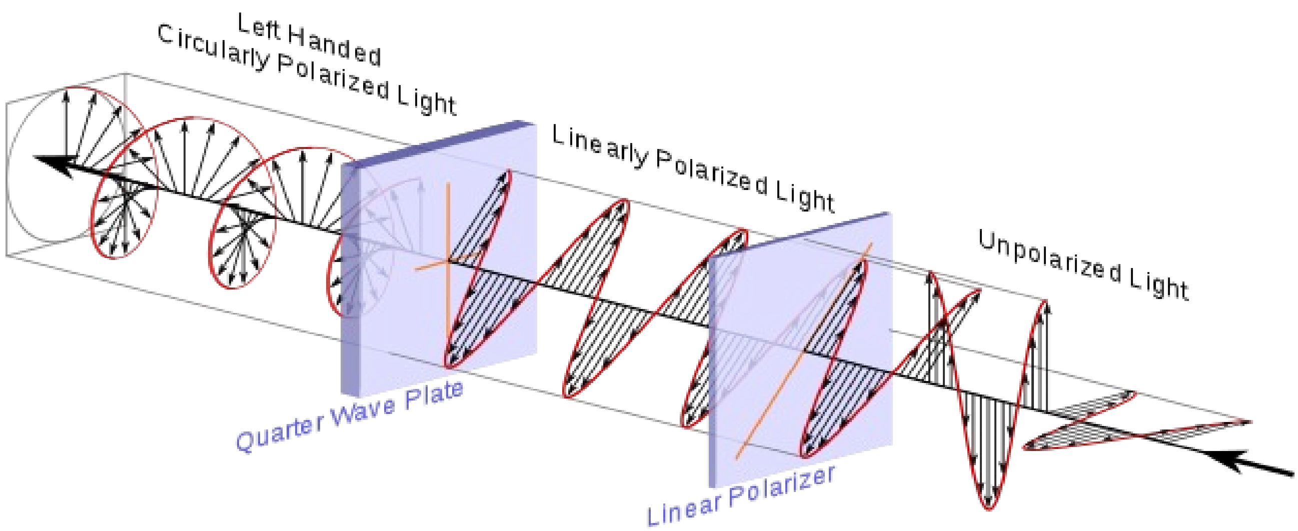
- Creating particles:
  - Whatever method you choose: make only a dozen particles before checking them between polarizers to see if the quality is good enough.
  - Machinists' punch: These don't work well since they leave a little ledge at the bottom of each particle.
  - Band saw: you can cut strips and then cut crosswise to make polygonal particles. Tedious but functional.
  - Custom tooling: For circles, work with your machinists to make a custom "spinning cookie cutter" tool of the size(s) you want. They will need to lubricate with dish soap rather than the usual machine oil which degrades the polymer. The goal is to have smooth edges all the way down, and no frozen-in stresses.
  - Milling: A machinist with a computer-controlled mill can trace the outside of individual particles and make repeated custom shapes. Lots of material wasted by what is milled away. Again, use dish soap as a lubricant.
  - Laser cutter: works on acrylic but not PhotoStress or polyurethane (these materials break down due to the heat of the laser).
  - Water jet cutter: some folks have had success with hiring a local shop to do this, others have failed. You will need to work with them to find a way to minimize notches/tabs at the start/stop location.
  - Casting: 2-part mixes need to placed under vaccuum to eliminate bubbles. The companies provide advice on making releasable molds.

- Frozen-in stresses: these usually take the form of a bright ring around the outer edge of the particle, when viewed in a polariscope. It is sometimes possible to eliminate/reduce them by slow, gentle heating over days/weeks.

- Humidity effects: you can reduce humidity-based adhesion by a light dusting of baking powder.

Circular Polarizers

- What's a circular polarizer? It's a linear polarizer combined with a quarter-wave plate oriented with its axis ±45° to the polarization axis. The two possible directions (clockwise or anti-clockwise) are usually called "left" and "right", according to the direction the electric field vector rotates as the light propagates. A photoelastic analyzer consists of a pair of left and right polarizers (each with their quarter-wave plate facing inward towards the photoelastic materials). Polarized sunglasses are linear polarizers, and 3D movie glasses can be either linear or circular polarizers depending on the system. (Image Source: Wikimedia Commons)



- Correct installation: For darkfield operation you need one polarizer of each type, rotating one polarizer with respect to the other will *always maintain a dark* view through the pair. For lightfield operation you need two polarizers of the same type, the view is always light. If one polarizer is flipped inside out with respect to the other, then the view will go *alternately light and dark* as you rotate one with respect to the other. For reflecting polariscopes, having the both polarizer and the analyzer match gives a darkfield image. Using two linear polarizers (without the quarter-wave plate, typically available in physics optics demo kits), will also give provide some information about stresses. However, since the photoelastic response will depend on relative orientation of the stress and the polarization axis this is not as desirable.

- Visualizing Fringes: When a photoelastic (birefringent) material is placed between the two polarizers and subjected to stress, the stressed region rotates the polarization of light according to the amount of local of stress and the stress-optic coefficient of the material. This allows for light bands to develop against a dark background.

- Sources of polarizers: Companies go in and out of business and have highly variable sizes and prices. One current source is https://www.polarization.com/ but a little googling will give many options. Photography shops also sell filters sized and mounted for use on standard cameras lenses. Circular polarizers from a camera shop have their quarter-wave plate facing the camera sensor (the wrong side for a our purposes), so you will need to unscrew the mounting frame and flip the filter over within its holder to get the quarter-wave plate on the correct side of the filter.

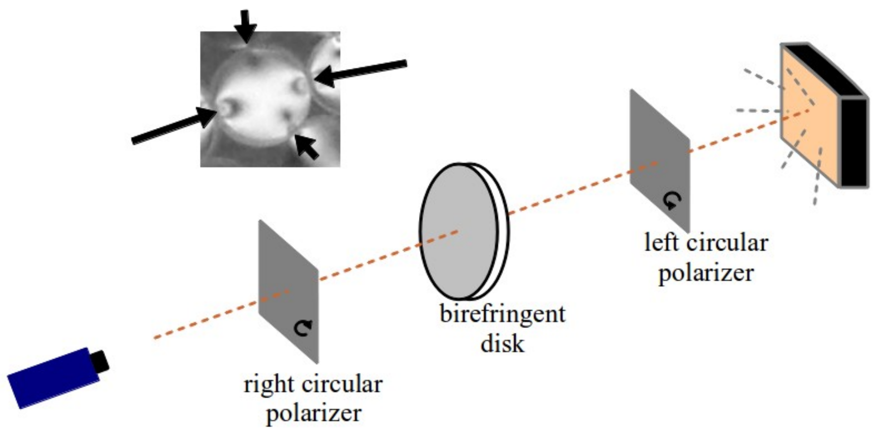
- http://www.apioptics.com/circular-polarizers.html
- http://www.edmundoptics.com/optics/polarizers/circular-polarizers/circular-polarizers/3624/
- 3D cinema glasses

- For more information on the underlying principles, see the "Technical References" listed at the end.

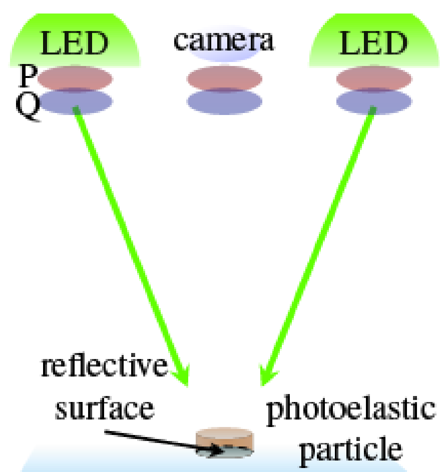
Building a Polariscope

Darkfield transmission polariscope: The schematic below document illustrates this configuration, which requires a uniform light source and a pair of left/right circular polarizers

- For a demo, you probably want a pair of full-sized left/right sheets so that everybody looks through the top sheet at the demo.
- For data-collection, use one sheet under the particles, and put the second polarizer directly on the camera. The second polarizer can be small enough to just cover the lens.



Reflection polariscope: If you cover one side of the particles with silver spray paint, it will reflect the incident light and simultaneously flip its polarization. Therefore, both the illumination source and the camera/eye will use the same (either left or right) circular polarizer. In the schematic at right, "P" is a linear polarizer and "Q" is a quarter-wave plate: all three are the same (either left or right) circular polarizer. (Image Source: Puckett 2012)



Using monochromatic light: Since the stress-optic coefficient of a birefringent materials depends on the wavelength of light, it is best to record monochromatic light for quantitative results. There are two main ways to do this. (1) Use colored LED lights. (2) Filter the light reaching the camera. This could be either a screw-on filter that attaches to the camera lens (possibly in series with the polarizer), or by just analyzing one RGB channel of a full-color image.

Lighting Sources: For a transmission polariscope, it is common to use a commercial lightbox to achieve uniform lighting. Two common types are a crafters' LED copy board (thin, rechargeable, no AC flicker) or a doctor's x-ray light box (available used on eBay, have 60 Hz flicker unless you buy a high-end one that has eliminated it). For a reflection polariscope, many other options are possible, including colored LED sources for monochromatic light. In all cases, be sure to use LED/fluorescent bulbs (these are cool to the touch) rather than halogens/incandescent (will heat the experiment as well as illuminate it). To also perform particle-tracking, it will be necessary to switch between two different sources of light (polarized, unpolarized) to visualized either the particle edges or their photoelastic response.

Fitting Contact Forces

The photoelastic response of many basic shapes is known analytically (Frocht 1941). A description of how to use this informtation to obtain vector contact forces is provided in two PhD theses: Majmudar (2006) and Puckett (2012). An open-source photoelastic solver for circular disks is provided here: http://nile.physics.ncsu.edu/pub/peDiscSolve/

Technical References

- https://en.wikipedia.org/wiki/Photoelasticity
- Max Frocht. *Photoelasticity*. (John Wiley & Sons, 1941).
- Eugene Hecht. *Optics.* (Addison-Wesley, 2001)
- Trushant Majmudar. PhD Thesis. Duke University. (2006). http://www.phy.duke.edu/~jt41/MYDKTH.pdf
- James Puckett. PhD Thesis. NC State. (2012) http://www.lib.ncsu.edu/resolver/1840.16/7998
- Brian Utter. "Photoelastic Materials." in *Experimental and Computational Techniques in Soft Condensed Matter Physics.* (Cambridge University Press, 2010).
- *Handbook of Granular Materials.* Scott Franklin and Mark Shattuck, eds. (CRC Press, 2015)