An overview of the use of laser ultrasonics to estimate the elastic properties of solid materials

Kasper van Wijk, Jonathan Simpson, Ludmila Adam, Jami Shepherd, James Loveday, Sam Hitchman

Physical Acoustics Laboratory and Dodd Walls Centre
Department of Physics, University of Auckland

September, 2019
From Cargese and FIFA 2002….
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(Klauss Littmann, 2019)
Waves and applications

**Applications**

- Imaging/monitoring
- Auckland Volcanic Field
- Reservoir characterisation
- Fruit/timber characterization
- Medical imaging
- Ice physics

**Methods**

- Surface and body wave tomography
- Full waveform sonic logging
- Laser ultrasound
- Acoustics
- Resonant ultrasound spectroscopy
- Photo-acoustics

**Frequency (Hz)**

- $10^{-1}$
- $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
Resonance on ice (with contacting transducers)
Resonance on ice (with contacting transducers)
Detecting small changes in (man-made poly-crystalline) ice

Vaughan et al. (The Cryosphere, 2016)
Elastic constants of ice

![Graph of Elastic Constants](image)

- **c11 (GPa)**
  - Values: 3.55, 3.65, 3.75, 3.85

- **c44 (GPa)**
  - Values: 11.8, 12.2, 12.6

- **Vp (km/s)**
  - Values: 3.3, 3.7, 4.1

- **Vs (km/s)**
  - Values: 2, 2.1, 2.2

Temperature (°C):
- -25, -20, -15, -10, -5, 1.9, 2.1, 2.2

**Graph a**: c11 and c44 vs. Temperature

**Graph b**: Vp and Vs vs. Temperature
Attenuation in ice

Extensional modes

Displacement models for each mode

-25°C

-5°C

Q (quality factor)

frequency (kHz)

e = extensional  t = torsional  f = flexural

Flexural mode  Torsional mode

van Wijk  Cargese, 2019  7/26
Monitoring the temperature in ice

- From -20 to -5 Celsius, we see *partial melt* in the pores
- This partial melt:
  - has an effect on the elastic parameters, particularly $c_{11} (v_p)$,
  - an even bigger effect on *attenuation* (mostly $Q_p$)
- The quality factor $Q$ is notoriously hard to estimate with seismic data, but has real potential for monitoring (fluids)
Non-contacting ultrasound with lasers
Non-contacting ultrasound with lasers

Pulsed Laser → Sample → Laser Doppler Vibrometer

Ultrasonic Elastic Waves → Recorded Waveform
Non-contacting ultrasound with lasers

Rotation and translation under computer control for source, receiver, and the sample

Pulsed Laser

Sample

Laser Doppler Vibrometer

Ultrasonic Elastic Waves

Recorded Waveform
Waves in two (approximate) spheres

Physics Today, October 2017
The modes of a sphere
The modes of a sphere
Apple-watching for 15 days
Laser Ultrasound, controlling pressure and temperature
The Alpine Fault, New Zealand

van Wijk | Cargese, 2019 | 14/26
Alpine Fault rocks

Decreasing distance to fault plane

Schist  Protomylonite  Mylonite  Ultramylonite  Cataclasite
Rotational scan under pressure
Pressure dependence

- Time (µs): 0, 5, 10, 15, 20, 25, 30
- Angle (degrees): 100, 150, 200
- Displacement (nm): -8.0, -4.0, 0.0, 4.0, 8.0

- Pressure levels: 1 MPa, 16 MPa
Rose diagrams

(a) Schist

\[
\bar{AV}_P = 18.7 \pm 1.0\%
\]

\[
\Delta AV_P = 1.3\%
\]

(b) Protomylonite

\[
\bar{AV}_P = 19.4 \pm 7.0\%
\]

\[
\Delta AV_P = 17.6\%
\]

(c) Mylonite

\[
\bar{AV}_P = 13.7 \pm 2.0\%
\]

\[
\Delta AV_P = 3.2\%
\]

(d) Ultramylonite

\[
\bar{AV}_P = 44.9 \pm 7.0\%
\]

\[
\Delta AV_P = 19.4\%
\]

(e) Cataclasite

\[
\bar{AV}_P = 12.4 \pm 2.0\%
\]

\[
\Delta AV_P = 5.2\%
\]
Anisotropy as a function of distance to the Alpine Fault
Conceptual cross-section of the Alpine Fault

- Foliation/mineral Alignment
- Microfractures

Alpine Fault
Principal Slip Surface

Footwall Sediments
Cataclasite
Mylonite
Ultramylonite

Scale: 200 m
The geothermal gradient of the Alpine Fault
Geothermal gradient in fault zones

![Diagram showing geothermal gradient and fault zones in New Zealand.](image-url)
Experimental Sensor

Fibre-optic temperature (and strain) sensing
Temperature dependence of elastic wave speed

![Graph showing temperature dependence of elastic wave speed](image-url)
Estimates of $v_p(P, T)$ in Alpine Fault rocks show the importance of fractures and the geothermal gradient. Furthermore, this information can be used to

1. Seismic imaging
2. Fault strength
Outlook of (laboratory) wave propagation research

- Elastic waves are sensitive probes of the physical properties of many solids:
  - Earth
  - timber
  - fruit
  - ice
  - the human body, others ...

and
Elastic waves are sensitive probes of the physical properties of many solids: Earth, timber, fruit, ice, the human body, others ... and

For applications in geophysics, seismic waves are sensitive to many things: composition, pressure, temperature, fractures, water content, others ...
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and

For applications in geophysics, \textit{seismic} waves are sensitive to many things:
- composition
- pressure
- temperature
- fractures
- water content, others ...

With laser ultrasound, we are poised to learn more about how each of these parameters control (seismic waves in and near) faults.