How can we approach the kHz range in laboratory rock physics?

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24th of April, 2017

Objective

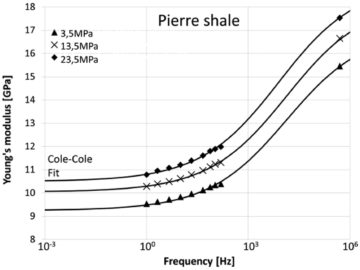

Figure: Modified from Szewczyk et al. (2016).

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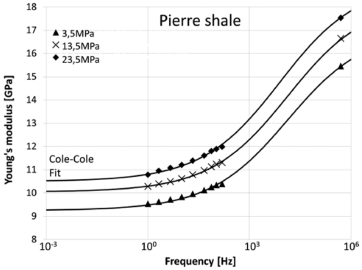


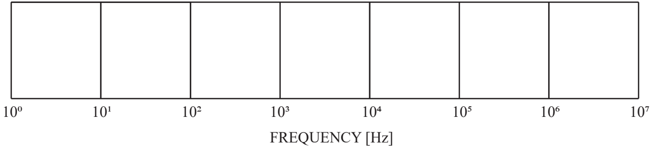
Figure: Modified from Szewczyk et al. (2016).

- In the words of Birch et al. (1938): "a respectable frequency gap remains to be bridged," as measurements between the seismic and the ultrasonic range are still quite rare.

Literature

Author(s)	Technique	Frequency [kHz]	Length [cm]	Diameter [cm]	Parameter(s)
Batzle et al. (2006)	FD	0.005-2.50	-	-	E, V_P, V_S Q_E
Birch et al. (1938)	RB	0.14-4.50	244	23.0	Q
Born (1941)	RB	0.93-12.8	14.00-124.0	12.0	$\delta = \pi Q^{-1}$
Bourbié et al. (1985)	RB	3.00-5.00	-	-	V_E, Q
Cadoret et al. (1995)	RB	1.00	110	8.00	V_E, V_S, V_P
Cadoret et al. (1998)	RB	1.00	110	8.00	Q_S, Q_E
Gardner et al. (1964)	RB	2.00-3.00	5.00-30.0	5.00	δ_E, δ_S
Goldberg et al. (1989)	RB	5.00-25.0	25.0	2.50	Q_P
Ide (1935)	RB	4.00-12.0	25.0	5.10	E
Jones et al. (1983)	RB	1.70-3.40	-	-	V, Q_S
Lucet et al. (1991)	RB	5.00-20.0	25.0-30.0	2.50	V_E, V_P, Q_E, Q_S
Lucet et al. (1992)	RB	3.00-10.0	30.0	2.50	Q_E
Lucet et al. (2006)	RB	2.00-20.0	-	-	Q_E, $V_{sonic}/V_{ultrasonic}$, V_{PP}/V_{PFB}
McCann et al. (2014)	PT	1.00-10.0	60.0	6.90	V_P, Q_P, T
Murphy (1982)	RB	0.30-14.0	20.0-100	-	V_S, V_E, Q_E, Q_S
Murphy (1984)	RB	5.00	20.0-25.0	19.0	V_S, V_E, Q_E, Q_S
Nakagawa et al. (2010)	SHRB	0.35-2.35	6.20	3.75	E, G, ν, V_P, V_S, Q
Nakagawa (2011)	SHRB	0.40-2.30	6.22	3.81	E, G, ν, V_P, V_S, Q
Nakagawa et al. (2011)	SHRB	0.30-1.50	7.62	3.75	E, G, ν, V_P, V_S, Q
O'Hara (1985)	RB	3.00-30.0	38.0	2.22	V_E, V_S, δ
Priest et al. (2006)	GHRC	<0.40	14.0	7.00	Q_E, Q_S
Tittmann (1977)	RB	22.0-23.0	-	-	Q_E, Q_S
Tittmann et al. (1981)	RB	7.00-9.00	12.0	1.50	Q_E
Waite et al. (2011)	SHRB	0.36-1.60	7.62	3.81	V_P, V_S
Wegel et al. (1935)	RB	0.10-100	∼30.0	∼1.00	Q_E, Q_S
Winkler et al. (1979)	RB	0.50-1.70	100	-	V_E, V_S, V_P, Q_E, Q_S, Q_K, Q_P
Winkler et al. (1982)	RB	0.50-9.00	100	-	V_E, V_S, V_P, Q_E, Q_S, Q_K, Q_P
Wyllie et al. (1962)	RB	>20.0	-	1.90-2.50	V_E, V_S, ν, δ_E, δ_S
Yin et al. (1992)	RB	1.60-1.80	39.0-53.0	5.00	E, Q_E
Zadler et al. (2004)	RUS	15.0-88.0	7.10	2.50	Q_E, Q_S, V_P, V_S

What is the kHz range and how do we measure it?



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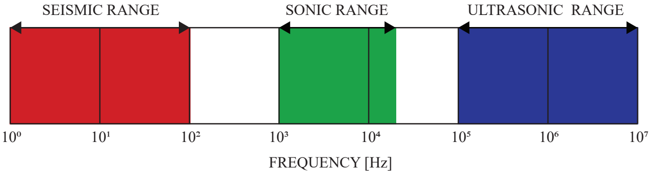

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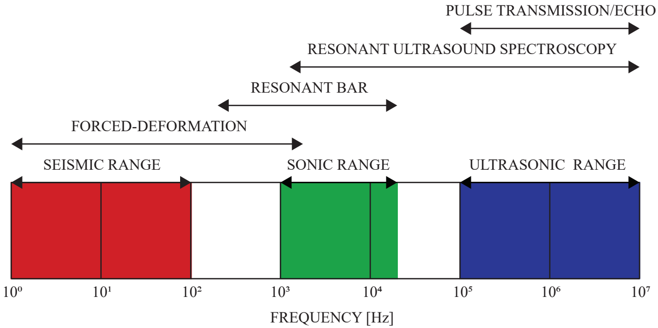

Resonant Bar Techniques

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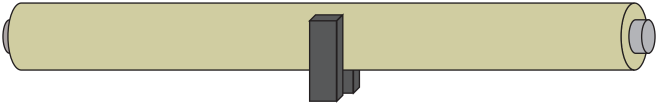

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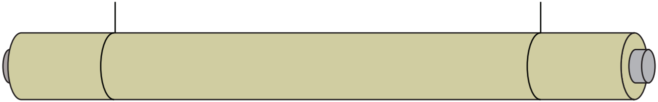

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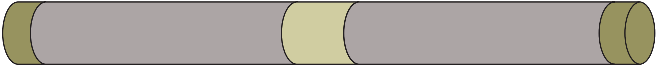

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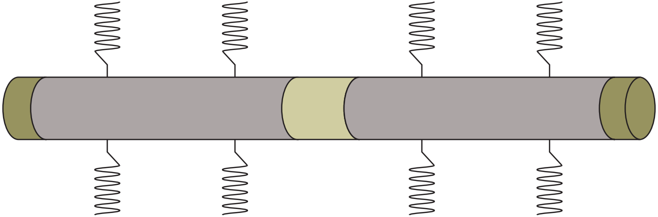
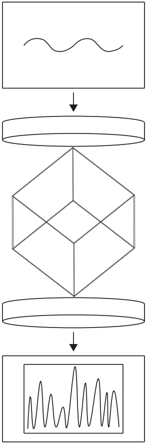


Resonant Ultrasound Spectroscopy (RUS)



Resonance Bar (RB) versus Resonant Ultrasound Spectroscopy (RUS)

RB and RUS are similar in the sense that they:

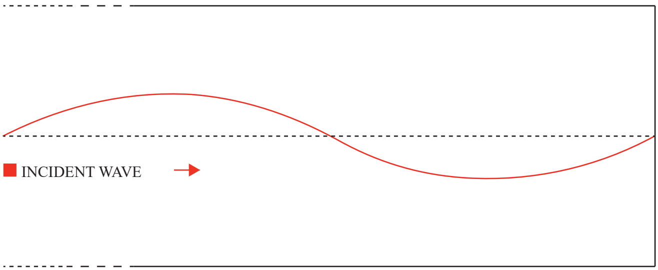
- overlap to some extent in terms of frequency range
- though RB is able to reach lower frequencies while RUS is able to measure higher frequencies (plus the range itself is larger)

Resonance Bar (RB) versus Resonant Ultrasound Spectroscopy (RUS)

That being said, differences arise as sample size and shape are considered:

- For RB measurements:
  - the most common sample is a bar that is cylindrical in cross-section with a length-to-diamter ratio of 10 or more
  - the length of the bars are anywhere from 10.0-100 cm
- Whereas for RUS:
  - the sample can be any shape that can be modelled, though most common are spheres, cylinders, and parallelpipeds
  - the size varies from a few hundred microns, with masses less than 100 micrograms, to several centimeters and several kilograms (Maynard, 1996)

What is resonance and how is it related to standing waves?



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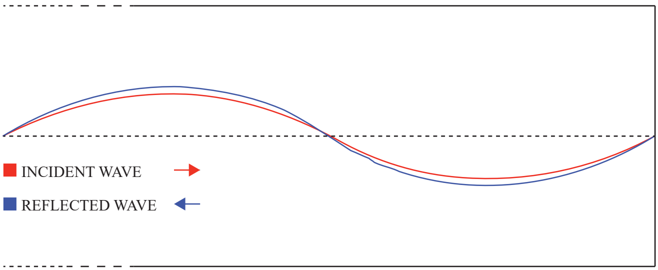

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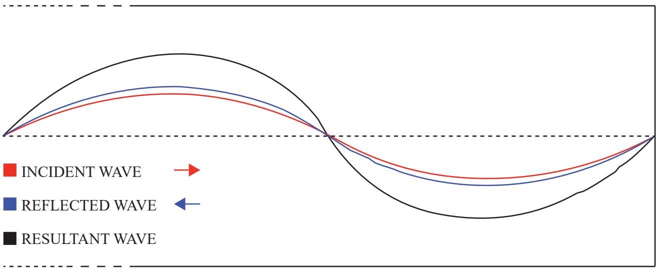

What are the different modes of vibration?

Mavko et al. (2009) defined the different modes of vibrations:

- **Extensional** waves depend on the displacement in both the radial and the axial domain (u_r and u_z)
- **Torsional** waves depend on displacement in the circumferential domain (u_θ)
- **Flexural** waves depend on displacement in both the axial and the circumferential domain (u_z and u_θ)

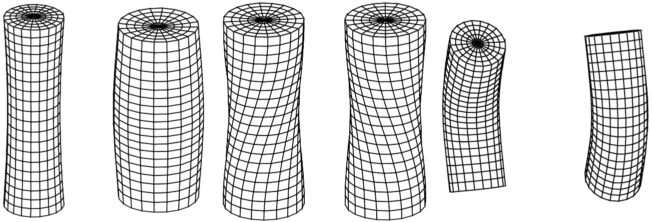

Figure: Modified from Zadler et al. (2004)

How are the velocities determined?

The general term from which the velocities are determined

$$v = \frac{2Lf}{n}, \tag{1}$$

whereas the extensional and torsional constituent of the resonating state occurs at different frequencies

$$v_S = \sqrt{\frac{\mu}{\rho}} = 2Lf_S, \tag{2}$$

$$v_E = \sqrt{\frac{E}{\rho}} = 2Lf_E. \tag{3}$$

How are the velocities determined?

In order to compute the P-wave velocity, the combined effort of the S-wave velocity and the Poisson's ratio is exploited

$$V_P^2 = \frac{2(\nu - 1)V_S^2}{2\nu - 1}, \tag{4}$$

$$\nu = \frac{V_E^2 - 2V_S^2}{2V_S^2} = \frac{1}{2}\sqrt{\frac{V_E}{V_S}} - 1, \tag{5}$$

while the combination of Equations 4 and 5 yields

$$V_P^2 = V_S^2 \frac{4V_S^2 - V_E^2}{3V_S^2 - V_E^2}. \tag{6}$$

What about attenuation?

For resonant bar measurements, two methods are widely used to determine the Q factor, namely the **half power** method and the **decay** method.

- The **half power** method exploits

$$Q = \frac{f_c}{\Delta f_c}. \quad (7)$$

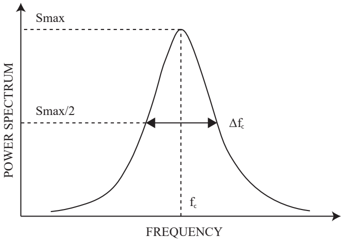

Figure: Modified from Nakagawa (2011).

What about attenuation?

- The **decay** method, on the other hand, is an alternative solution to monitor the decay of the resonation once the system is vibrating in a steady state and the driving force is switched off.

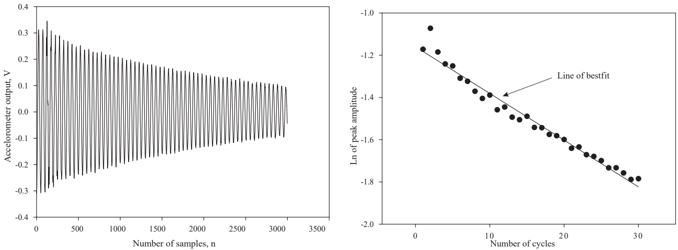

Figure: Modified from Priest et al. (2006)

What about attenuation?

- In a dissipative system, as the resonance response decays, the difference in amplitude between successive peaks is inferred as energy loss per cycle termed by the logarithmic decrement

$$\delta = \ln \frac{A_1}{A_2}, \tag{8}$$

whereas the intrinsic attenuation ($1/Q$) is related to the logarithmic decrement (δ) via

$$\frac{1}{Q} = \frac{\delta}{\pi}. \tag{9}$$

What do we want to do?

We want to conduct measurements in the sonic interval at certain levels of stress, temperature, and saturation; measurements under conditions that are similar to the ones imposed by the existing equipment.
Ideally, building a technique in the mould of Nakagawa would be preferable, but...

- design, build, and calibrate a new apparatus is both expensive and time consuming
- it would also be difficult to perform resonant experiments under the desired conditions

We can therefore not help but ask ourselves...

- is it possible to surpass the 150 Hz threshold set by Szewczyk et al. (2016) due to resonance occurrences?
    - perhaps it is possible to do measurements between the resonances?

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Acknowledgement