Ultrasonic evaluation of the hydration degree of the orange peel

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Fruit Structure 2015. Angers, November 31th 2015

Ultrasound characterization of fruits

- Goal
  - **Monitoring quality of fruits in post-harvest processes using ultrasound**
  - Find correlation:

    Acoustical magnitude ←→ Quality index

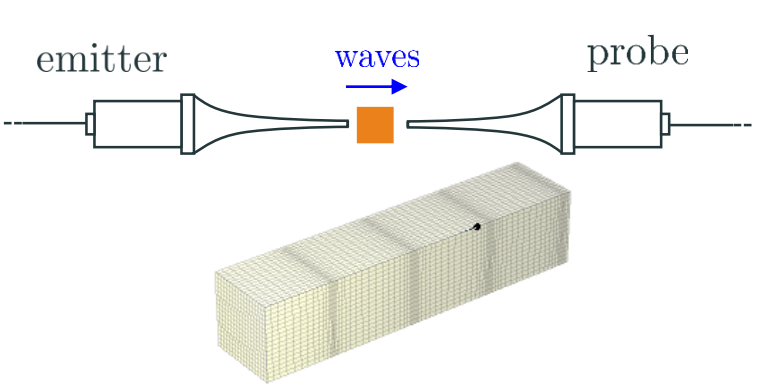
Acoustic
sound speed
attenuation
… dispersion curves

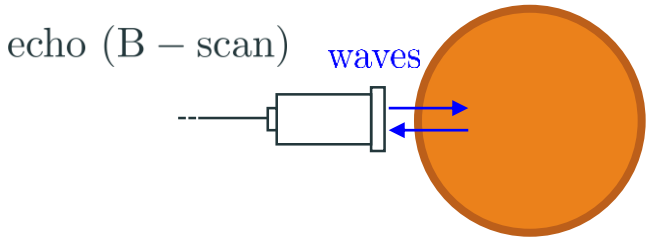
Quality index
firmness
turgidity
… hydration
… acidity

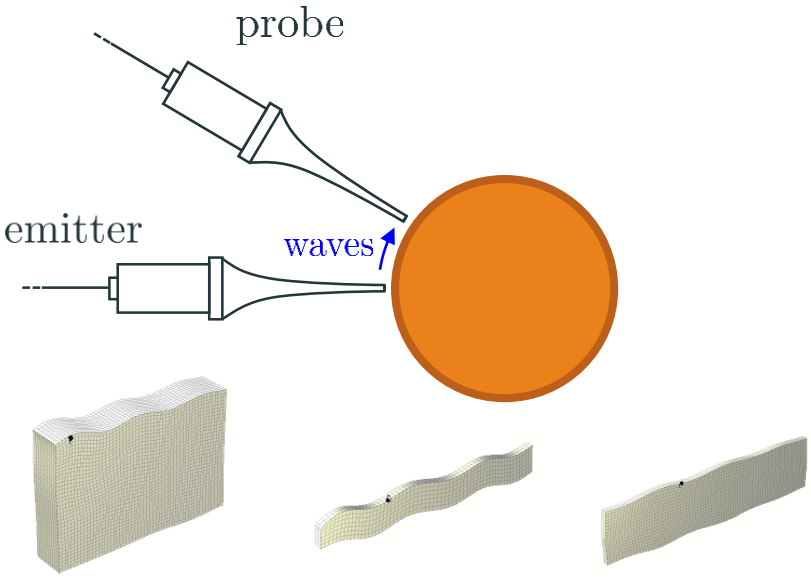
A better understanding of the elastodynamic behavior of the fruit tissues is needed

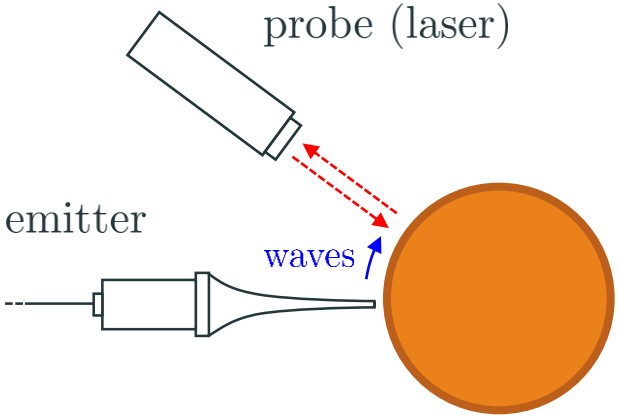
CONFIGURATIONS

- Experimental tests:



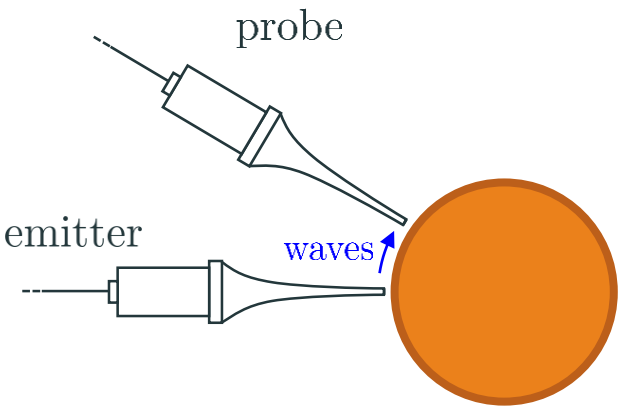


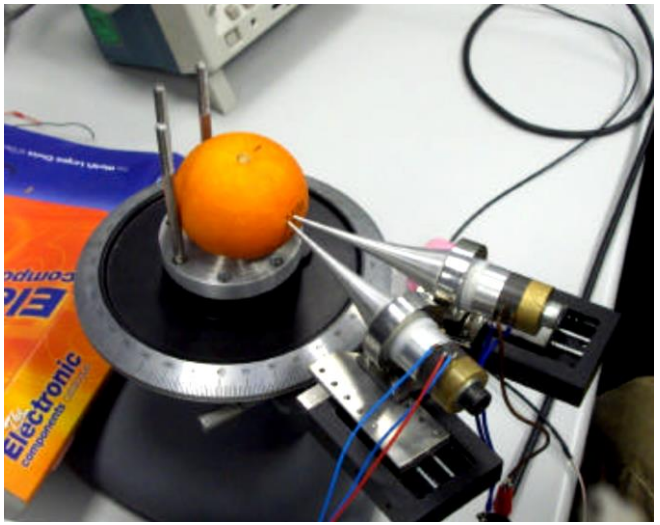




Experimental set-up

- Set-up parameters:
  - 40 kHz piezoelectric transducer
  - Horn-type mechanical amplification:
  - high stress / small displacement → small stress / high displacement
  - Emitter / receiver configuration
- Measure:
  - Measure at equally-spaced locations -> sound speed + attenuation
  - Dehydration was also measured (net weight loss)
  - Repeat process over two orange varieties (Navelina and Ortanique)
  - Total time 65 days

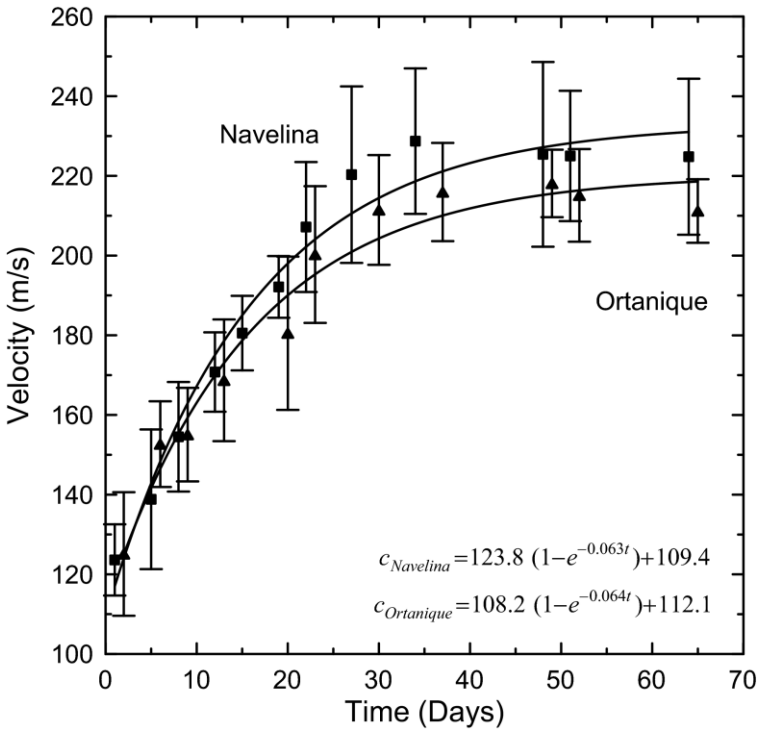




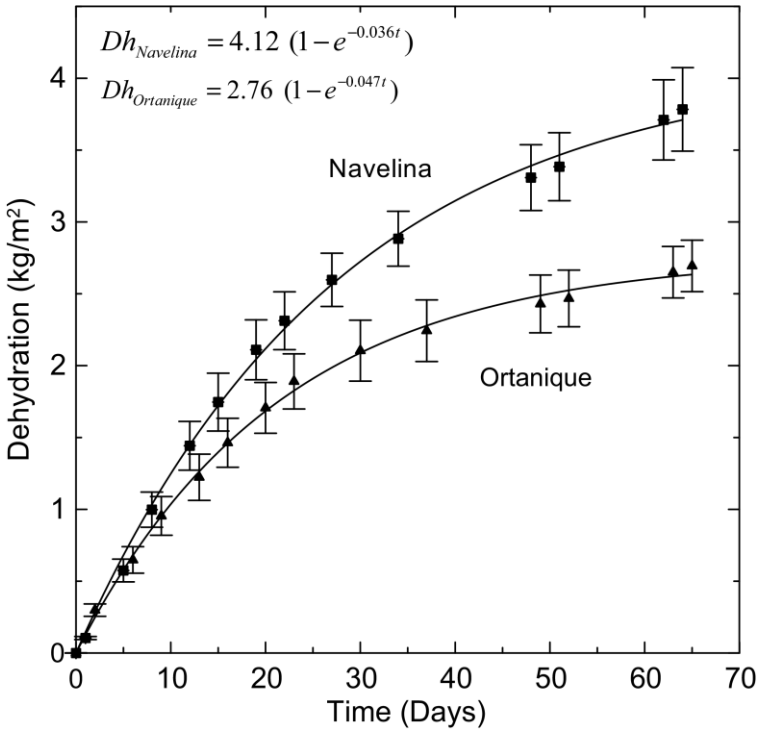
Ultrasound characterization of fruits

- Experimental results:

Ultrasound



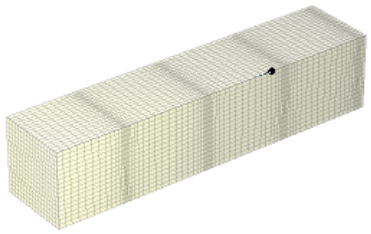
Dehydration (Quality Index)



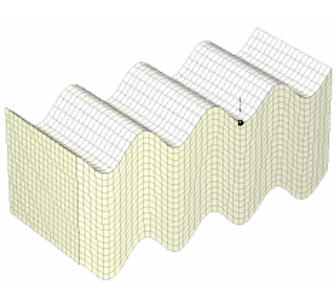
How does it relate to elasticity?
Identify the nature of the waves

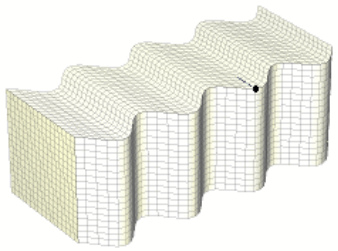
ELASTIC PARAMETERS

- Pure longitudinal $c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}}$



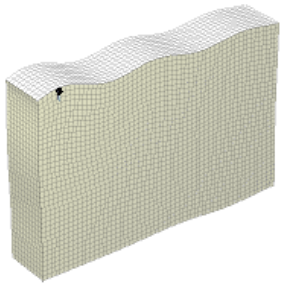
- Pure shear $c_S = \sqrt{\frac{\mu}{\rho}}$



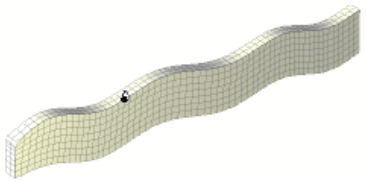


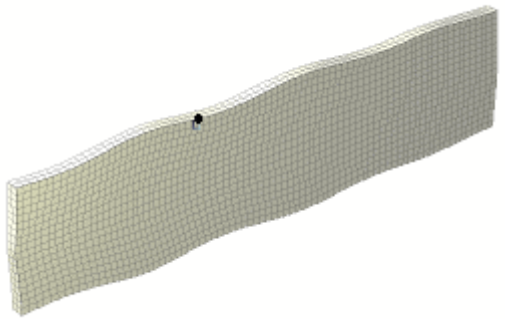
- Other: Surface Rayleigh waves, Lamb plate modes, Love waves …

$c_R = f(c_S, \nu)$



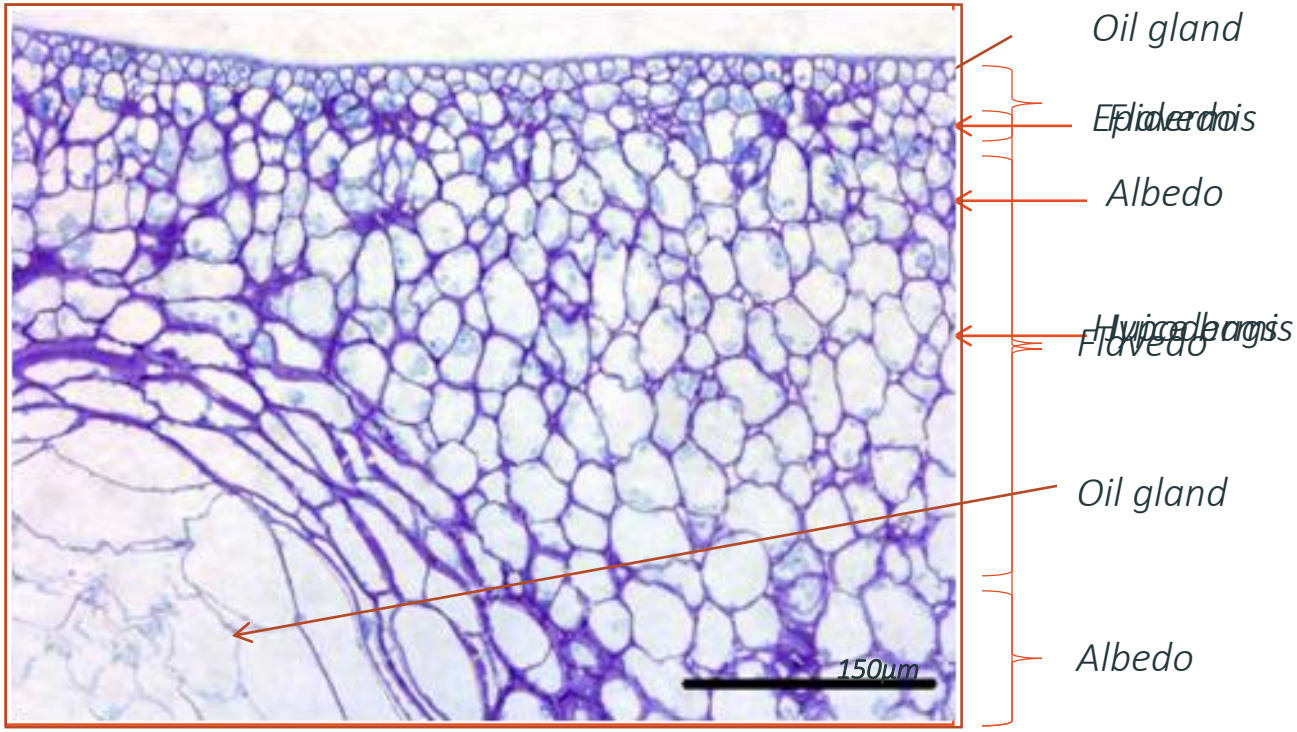
$c_{Lamb} = f(\omega, k)$





Numerical Simulations

- Citric: Morphology



Heterogeneous media: Solids structures, liquids, porous layers and gases
Water-like media: The peel is rich in water content

Numerical Simulations

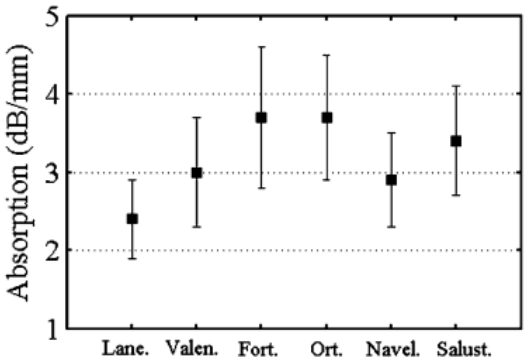
- Hypothesis:
  1. Measured waves are Rayleigh surface waves:
     - The high damping of the porous Albedo layer inhibit the generation of standard Lamb-type waves
  2. The orange skin is a water-like media
     1. Poisson's coefficient is close to 0.5 $\rightarrow c_R = \beta c_s \qquad \beta \approx 0.95$
     2. Exist a longitudinal wave $\rightarrow c_L \approx c_{\text{water}}$

$$\mu = \rho \left(\frac{c_R}{\beta} \right)^2 \qquad \lambda = \rho c_L^2 - 2\mu$$

Media	Measured density ρ (kg/m^3)	Young Modulus E (MPa)	Poisson coefficient v	Longitudinal propagation speed (m/s)	Measured Propagation speed (m/s)	Calculated Rayleigh surface wave
Orange Peel	903	107,7	0,491	1540	130-240	200

Numerical Simulations

- Elastodynamic FDTD simulations in spherical coordinates
  - Model: linear elastic, stress / velocity formulation



Post.Biol.Tech. 43 (2007) 115–120

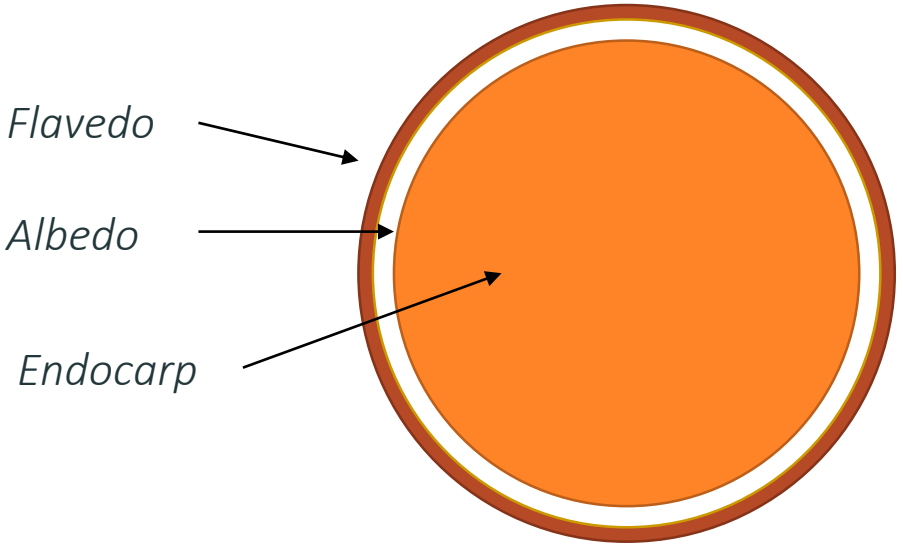


Table 2
Mechanical parameters used in the simulations for the two models.

Parameter	Air	Flavedo	Albedo	Inner core
Density, ρ (kg/m^3)	1.21	903	820	978
Lame's 1°, λ (MPa)	0.142	1.95×10^3	0.62×10^3	2.2×10^3
Lame's 2°, μ (MPa)	0	36	10.8	0
Young modulus, E (MPa)	–	107.3	22.2	–
Poisson's ratio, ν	–	0.491	0.25	–

Numerical Simulations

- Elastodynamic FDTD simulations in spherical coordinates
  - Model: linear elastic, stress / velocity formulation

Particle velocity

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\gamma_v \mathbf{v}\right)=\nabla\cdot\boldsymbol{\sigma}$$

Stress

$$\rho\left(\frac{\partial \boldsymbol{\sigma}}{\partial t}+\gamma_\sigma \boldsymbol{\sigma}\right)=\lambda\bar{\mathbf{I}}\left(\nabla\cdot\mathbf{v}\right)+\mu\left(\nabla\mathbf{v}+\mathbf{v}\nabla\right)$$

Numerical Simulations

- Elastodynamic FDTD simulations in spherical coordinates
  - Model: linear elastic, stress / velocity formulation

Particle velocity

$$\rho\frac{\partial v_r}{\partial t} = \frac{\partial \sigma_{rr}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_{r\theta}}{\partial \theta} + \frac{1}{r\sin\theta}\frac{\partial \sigma_{r\varphi}}{\partial \varphi} + \frac{2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\varphi\varphi} + \sigma_{r\theta}\cot\theta}{r}$$

$$\rho\frac{\partial v_\theta}{\partial t} = \frac{1}{r}\frac{\partial \sigma_{\theta\theta}}{\partial \theta} + \frac{\partial \sigma_{r\theta}}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial \sigma_{\theta\varphi}}{\partial \varphi} + \frac{3\sigma_{r\theta} + (\sigma_{\theta\theta} - \sigma_{\varphi\varphi})\cot\theta}{r}$$

$$\rho\frac{\partial v_\varphi}{\partial t} = \frac{1}{r\sin\theta}\frac{\partial \sigma_{\varphi\varphi}}{\partial \varphi} + \frac{\partial \sigma_{r\varphi}}{\partial r} + \frac{1}{r}\frac{\partial \sigma_{\theta\varphi}}{\partial \theta} + \frac{3\sigma_{r\varphi} + 2\sigma_{\theta\varphi}\cot\theta}{r}$$

Normal Stress

$$\frac{\partial \sigma_{rr}}{\partial t} + \eta_P \sigma_{rr} = \lambda\left(\frac{\partial v_r}{\partial r} + \frac{2}{r}v_r + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{\cot\theta}{r}v_\theta + \frac{1}{r\sin\theta}\frac{\partial v_\varphi}{\partial \varphi}\right) + 2\mu\frac{\partial v_r}{\partial r}$$

$$\frac{\partial \sigma_{\theta\theta}}{\partial t} + \eta_P \sigma_{\theta\theta} = \lambda\left(\frac{\partial v_r}{\partial r} + \frac{2}{r}v_r + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{\cot\theta}{r}v_\theta + \frac{1}{r\sin\theta}\frac{\partial v_\varphi}{\partial \varphi}\right) + 2\mu\left(\frac{v_r}{r} + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta}\right)$$

$$\frac{\partial \sigma_{\varphi\varphi}}{\partial t} + \eta_P \sigma_{\varphi\varphi} = \lambda\left(\frac{\partial v_r}{\partial r} + \frac{2}{r}v_r + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{\cot\theta}{r}v_\theta + \frac{1}{r\sin\theta}\frac{\partial v_\varphi}{\partial \varphi}\right) + 2\mu\left(\frac{v_r}{r} + \frac{\cot\theta}{r}v_\theta + \frac{1}{r\sin\theta}\frac{\partial v_\varphi}{\partial \varphi}\right)$$

Shear Stress

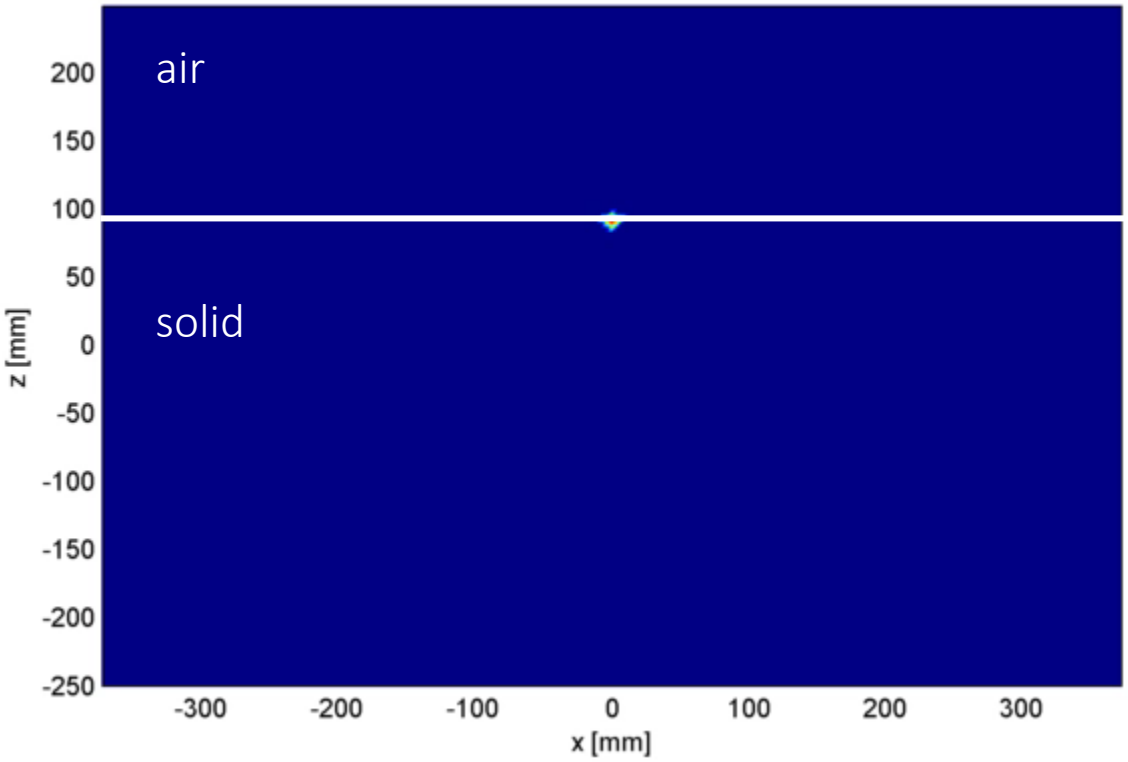
$$\frac{\partial \sigma_{r\theta}}{\partial t} + \eta_S \sigma_{r\theta} = \mu\left(\frac{1}{r}\frac{\partial v_r}{\partial \theta} - \frac{v_\theta}{r} + \frac{\partial v_\theta}{\partial r}\right)$$

$$\frac{\partial \sigma_{r\varphi}}{\partial t} + \eta_S \sigma_{r\varphi} = \mu\left(\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial \varphi} - \frac{v_\varphi}{r} + \frac{\partial v_\varphi}{\partial r}\right)$$

$$\frac{\partial \sigma_{\theta\varphi}}{\partial t} + \eta_S \sigma_{\theta\varphi} = \mu\left(\frac{1}{r\sin\theta}\frac{\partial v_\theta}{\partial \varphi} + \frac{1}{r}\frac{\partial v_\varphi}{\partial \theta} - \frac{\cot\theta}{r}v_\varphi\right)$$

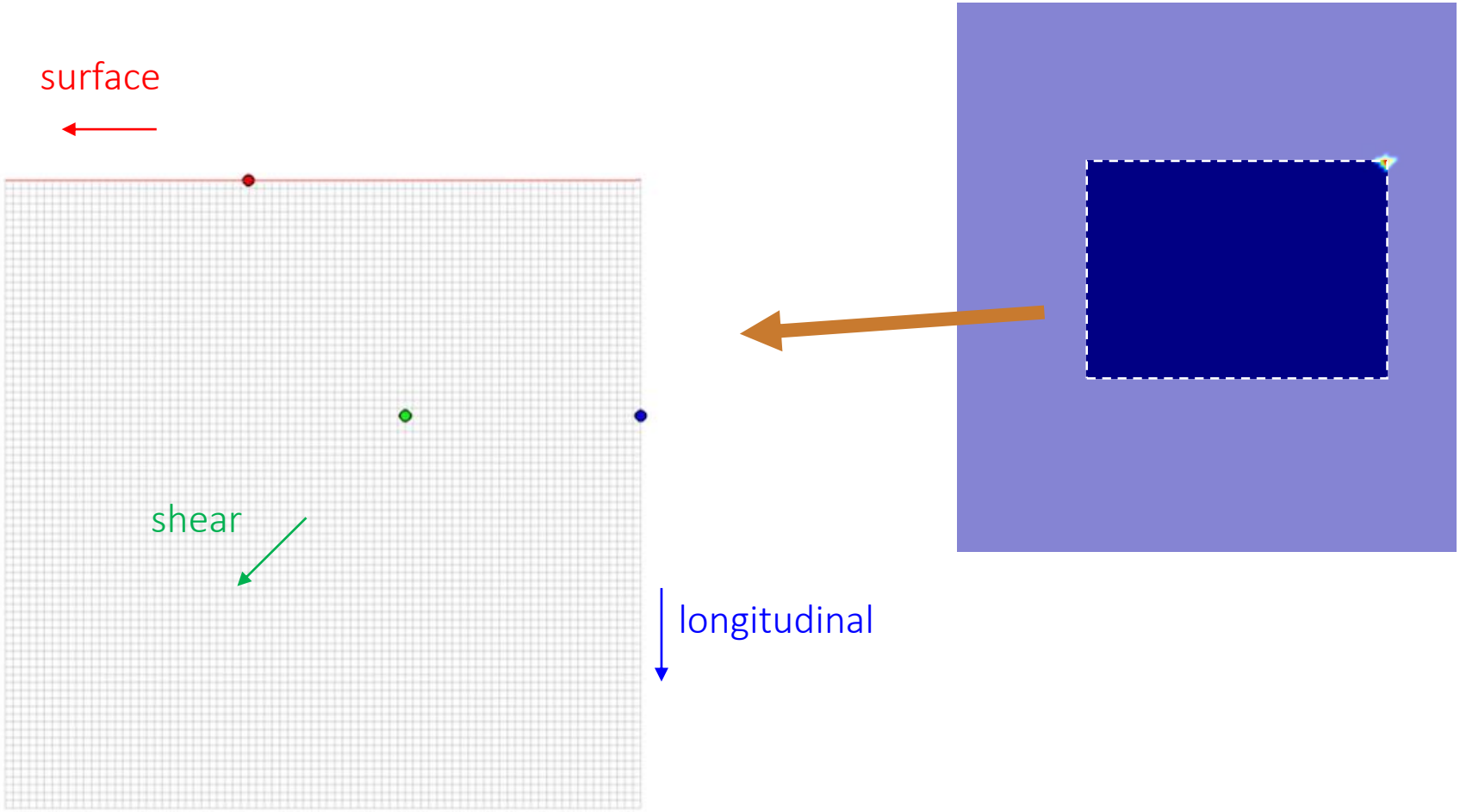
Numerical Simulations

- Elastodynamic FDTD simulations in spherical coordinates
  - Model: linear elastic, stress / velocity formulation



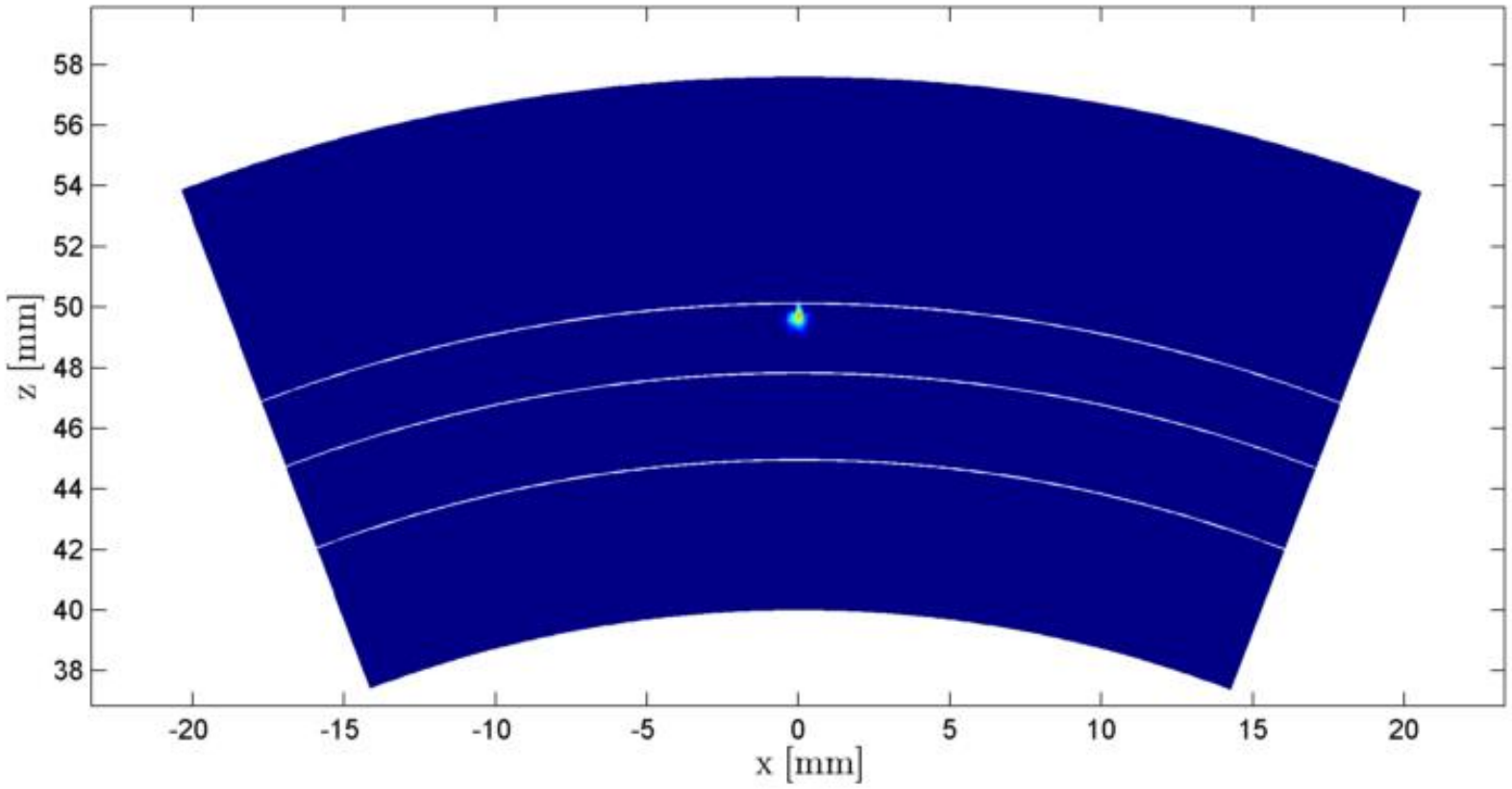
Numerical Simulations

- What kind of wave / mode we can measure at the surface?



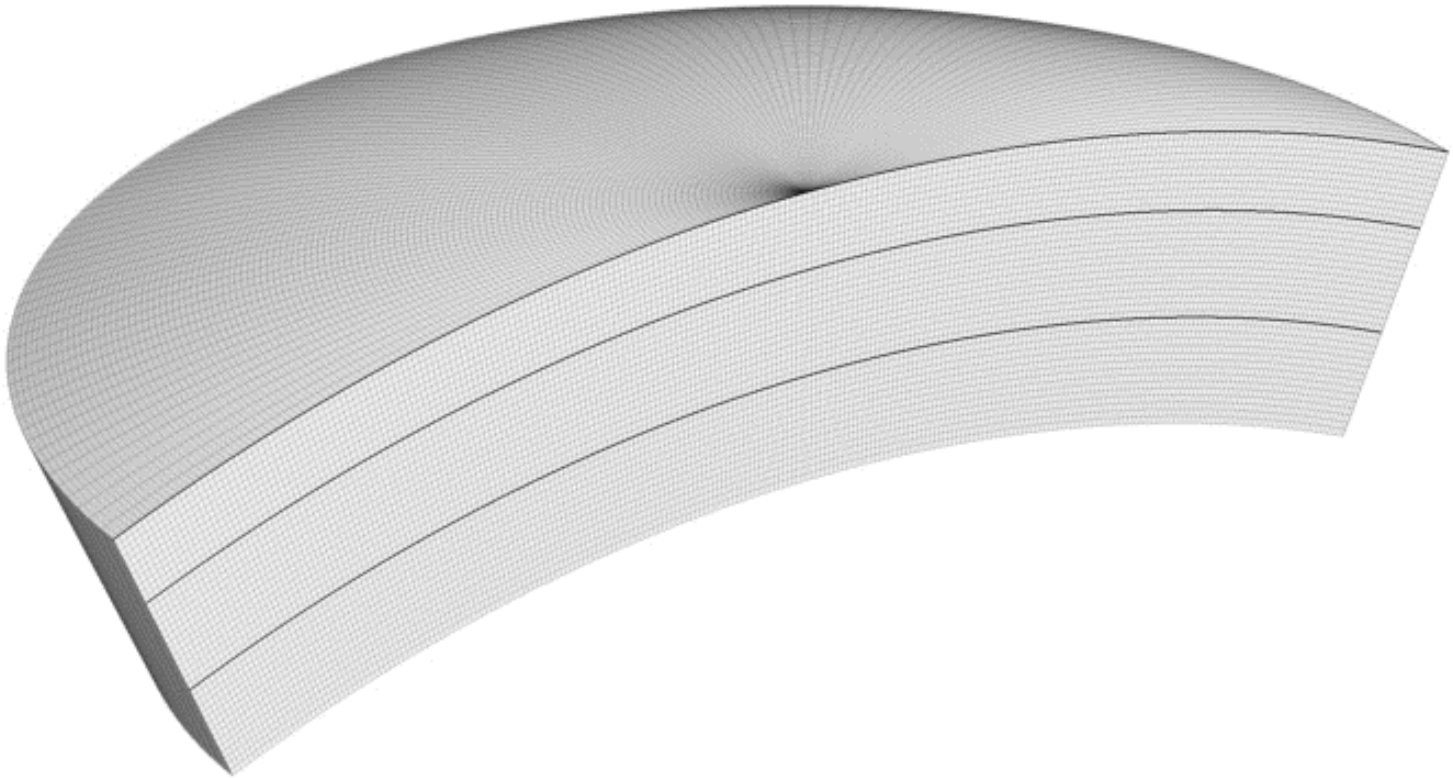
Numerical Simulations

- What kind of wave / mode we can measure at the surface?



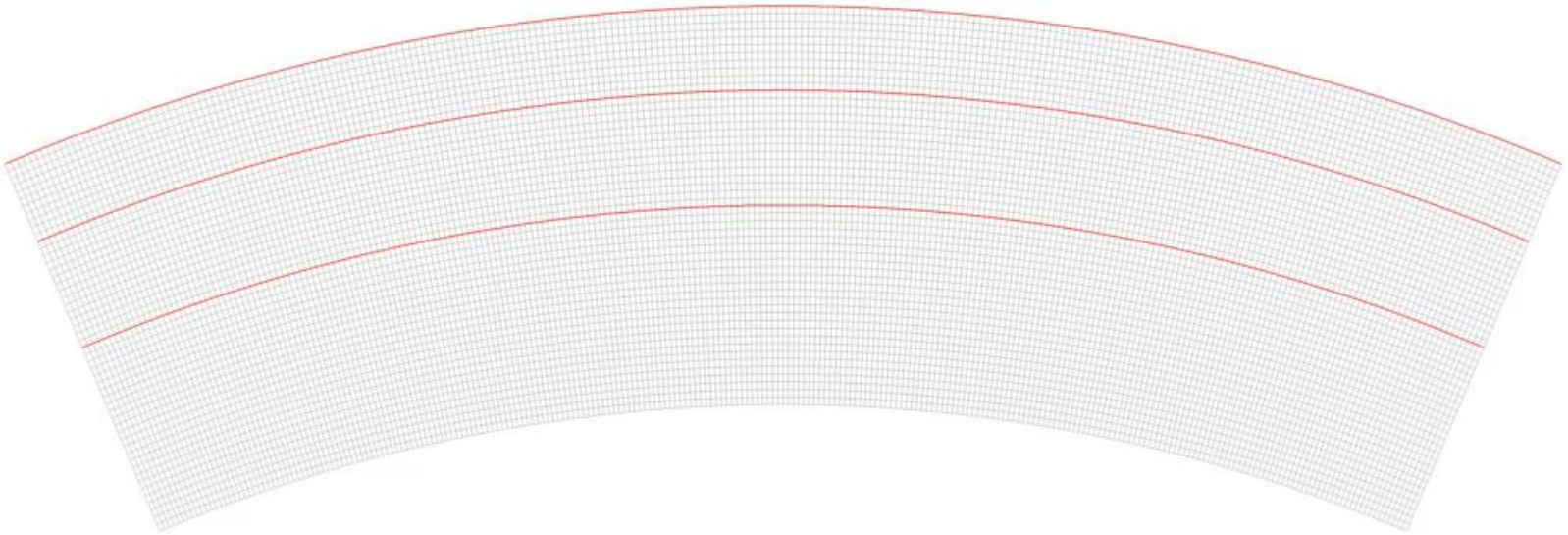
Numerical Simulations

- What kind of wave / mode we can measure at the surface?



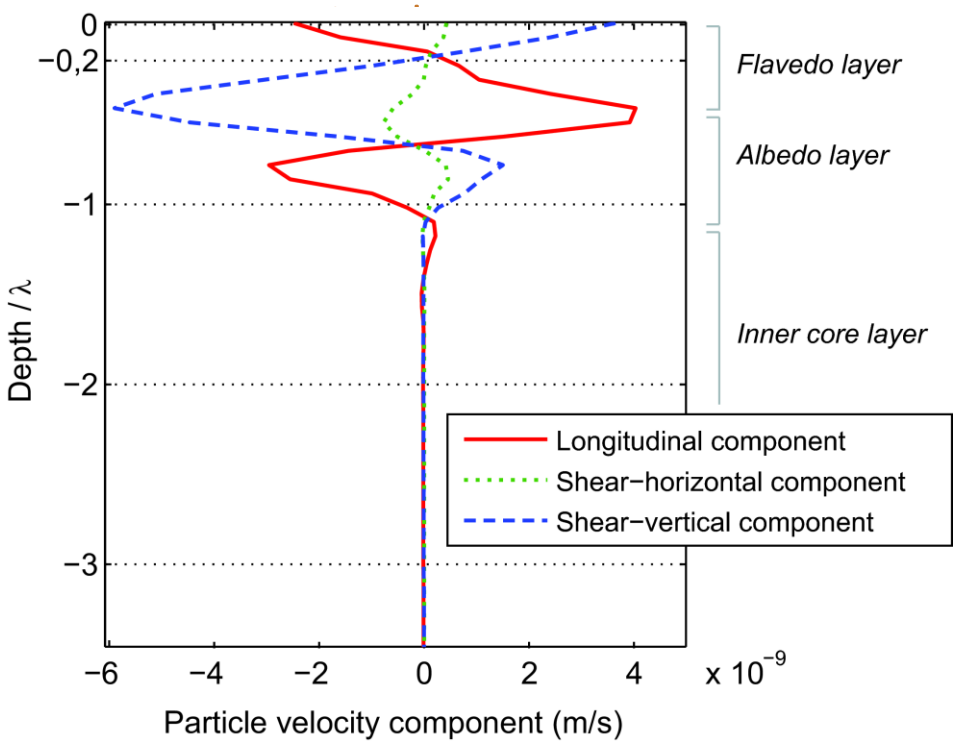
Numerical Simulations

- What kind of wave / mode we can measure at the surface?

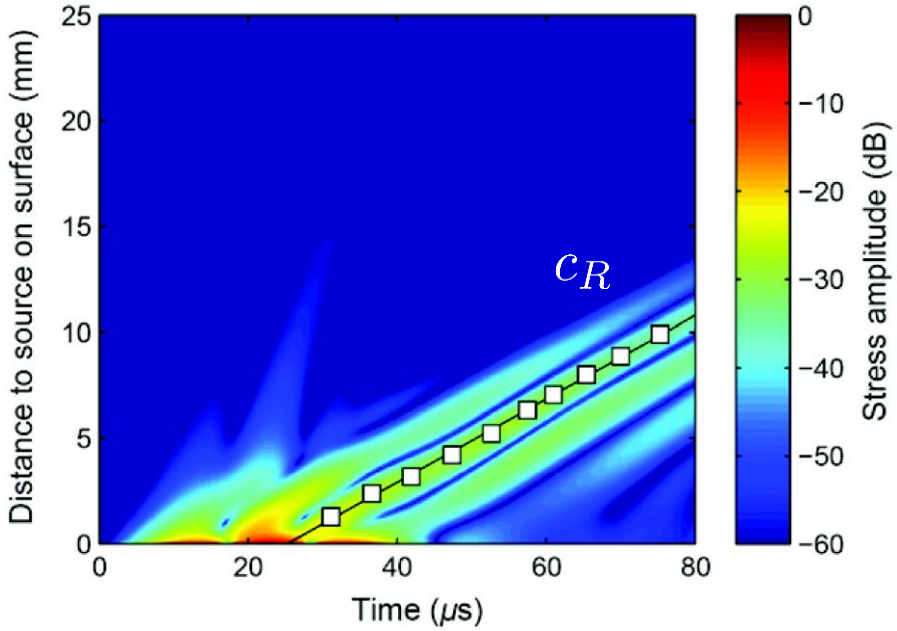


Numerical Simulations

- What kind of wave / mode we can measure at the surface?



Attenuation



1. Can't penetrate at depth>λ
2. Motion inversion below 0,2 λ
3. No motion at 0,2 λ

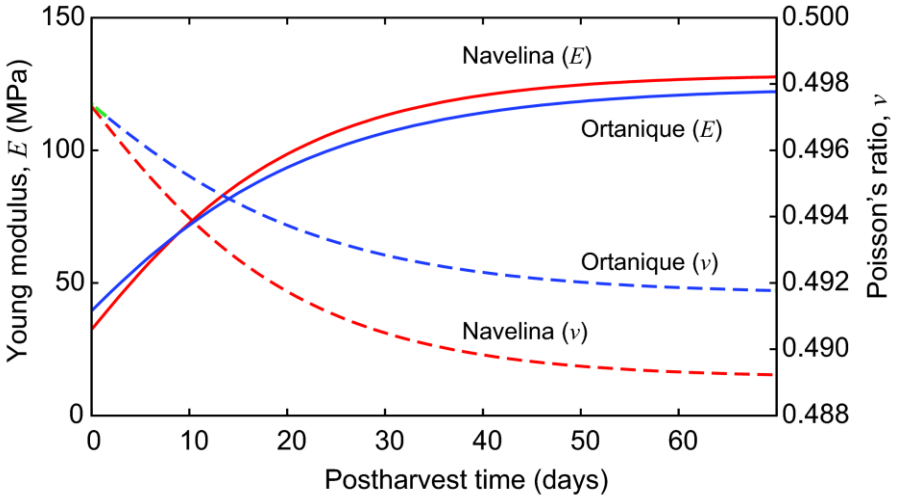
Models

- Assuming we measure **Rayleigh surface waves** and $\nu \to 0.5$ $\beta = c_R/c_S \approx 0.95$

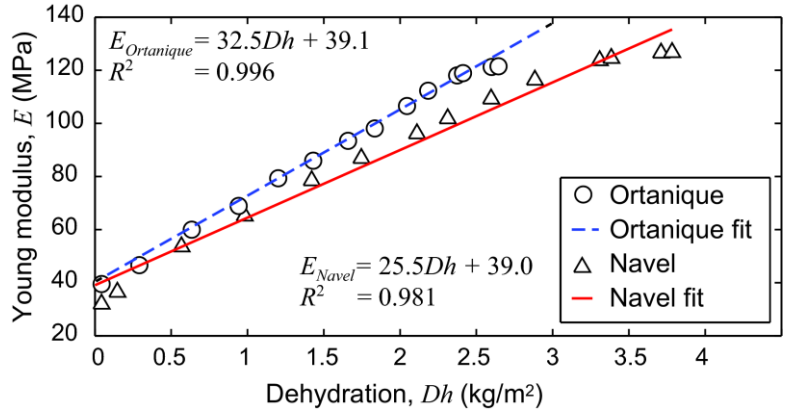
$$E = \rho \frac{-3c_L^2(\beta c_R)^2 + 5(\beta c_R)^2}{(\beta c_R)^2 - c_L^2}$$

$$\nu = \frac{c_L^2 - 2(\beta c_R)^2}{2c_L - 2(\beta c_R)^2}$$

Model:
Elasticity → post harvest time



Model:
Ultrasound → Quality Index



Summary and Conclusions

- "Some" waves can be excited and detected on the surface of the fruit
  - Ultrasound wave speed (200 m/s)
  - Attenuation (3 dB/cm)
- FDTD simulations show that at surface the wave motion is a Rayleigh-like surface mode
- Assuming orange peel is a soft media ($\nu \rightarrow 0.5$) the elasticity can be obtained by a linear elastic model

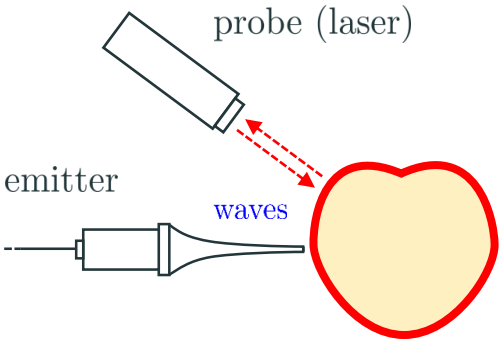
- **Elasticity can be estimated by ultrasound**
- **Dehydration is strongly correlated to elasticity:** Ultrasound -> Quality factor

Future lines

- **Orange's albedo:**
  - Porous media filled with gases
  - High absorption (6dB/mm)
- Restrict the measurement to the peel
- Hard to test the elasticity of the inner structure



- **Apples**
  - Surface elastic waves are affected by the bottom layer
  - Potential to explore the flesh of the fruit





References

N. Jiménez et al. / Ultrasonic evaluation of the hydration degree of the orange peel. **Postharvest Biology and Technology** 67 (2012) 130–137

F. Camarena, J.A. Martinez-Mora / **Journal of Food Engineering** 75 (2006) 503–507

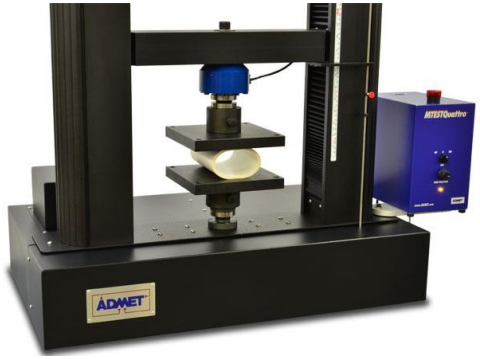
F. Camarena et al. / **Postharvest Biology and Technology** 43 (2007) 115–120

Mizrach, A., 2008. Ultrasonic technology for quality evaluation of fresh fruit and vegetables in pre- and postharvest processes. **Postharvest Biol. Technol**. 48, 315–330.

Thanks for your attention

Discussion

- Stress / strain mechanical tests

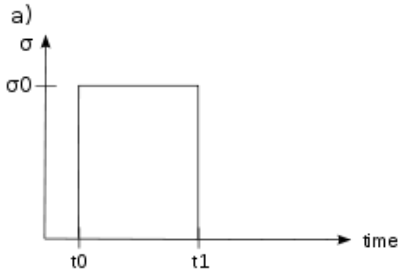


Medium	[Experiment] Sound speed (m/s)	[Experiment] Density ρ (kg/m³)	[Bibl.] Young modulus E (MPa)	[Bibl.] Poisson coefficient V	[Estimated] Longitudinal wave speed C_L (m/s)	[Estimated] Shear wave speed C_S (m/s)
Orange	130-240	903	1,57*	0,34*	82,7	54,6
Avocado	150-400	963	0,48*	0,33*	32,1	18,2
Apple	98-183	1003	3,33*	0,17*	65,1	36,5
Melon	61-90	1209	5,54*	0,30*	76,4	49,6
Potato	686,89	1087	7,14*	0,25*	60,8	34,1
Carrot	341-500	1021	6,96*	0,30*	104,1	64,1

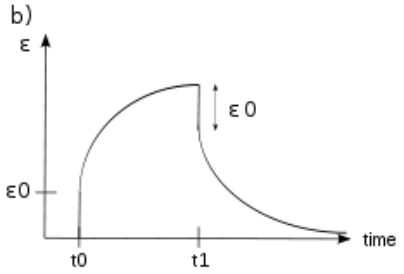
** Elastic parameters measured with stress-strain techniques (Singh, 2006), (Baryeh, 2000)(Grotte, 2002)(Jindal, 1985)(Bunyaphlann, 1973). Ultrasonic measured acoustics parameters (Mizrach, 2008)*

VISCOELASTICITY

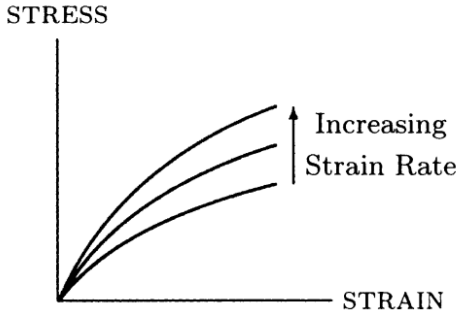
Elastic



Viscoelastic

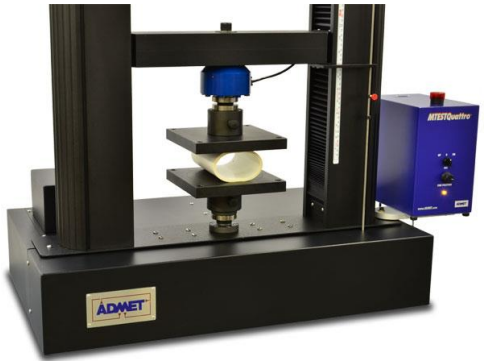


Applied stress and induced strain are functions of time over a short period for a viscoelastic material.



Stress-strain techniques

Long time strain variations (**≈Hz**)



Ultrasound techniques

"Very" short time strain variations

40 kHz!!!

Media dispersion

$$\alpha(\omega) = \alpha_0 \omega^{\gamma}$$

$$\frac{1}{c_p(\omega)} = \frac{1}{c(\omega_0)} + \alpha_0 \tan\left(\frac{\pi\gamma}{2}\right)\left(|\omega|^{\gamma-1} - |\omega_0|^{\gamma-1}\right)$$

