Effective elastic constants of layered vegetal parenchyma tissues and sclerenchyma fibres, relationship with cellular microscopic features. Non-invasive ultrasonic techniques.

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ITEFI, Spanish National Research Council.
CSIC
Overview

I. Through transmission: Normal incidence, One layer approach
   Effective elastic properties of plant leaves

II. Through transmission: Normal incidence, Layered approach
    Effective properties of every layer.

III. Through transmission: Oblique incidence, Layered approach
     Shear properties.

IV. Guided waves: Properties of sclerenchyma fibers
I. Through transmission:
   Normal incidence
   One layer approach
   Effective properties
Experimental set-up through transmission.

Ultrasonic Tx and Rx that operate in air. Completely contactless and non-invasive.

Different length scales:

Measurement area 10-100 mm²

Wavelength: 100 – 800 μm

Displacements: nm scale

Ultrasound velocity & attenuation (0.2 – 1.5 MHz)

Excitation and sensing of leaf thickness resonances. One effective layer approach.

Upper epidermis
Pallisade parenchyma
Spongy mesophyll
Lower epidermis

Velocity = 348 m/s
Density = 1050 kg/m³
Thickness = 680 μm
Attenuation = 231 Np/m
Ultrasonic effective properties of plant leaves
Analysis of the first thickness resonance.

<table>
<thead>
<tr>
<th>Species</th>
<th>Density (kg/m³)</th>
<th>Resonant frequency (kHz)</th>
<th>Velocity (m/s)</th>
<th>Attenuation (Np/m)</th>
<th>$C_{33}$ (MPa)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prunus laurocerasus</em></td>
<td>780</td>
<td>275 ± 4 283 ± 4</td>
<td>255 ± 5 270 ± 15</td>
<td>910 ± 10 800 ± 70</td>
<td>48.9 + 13.1i 54.4 + 13.4i</td>
<td>1.5</td>
</tr>
<tr>
<td><em>Ligustrum lucidum</em></td>
<td>950</td>
<td>265 ± 4 260 ± 4</td>
<td>196 ± 3 287 ± 3</td>
<td>790 ± 10 416 ± 10</td>
<td>35.5 + 6.6i 77.0 + 11.3 i</td>
<td>1.9</td>
</tr>
<tr>
<td><em>Populus x. euroamericana</em></td>
<td>870</td>
<td>730 ± 4 598 ± 4</td>
<td>365 ± 5 351 ± 5</td>
<td>1420 ± 40 1140 ± 50</td>
<td>100.2 + 22.9i 92.8 + 20i</td>
<td>1.9</td>
</tr>
<tr>
<td><em>Platanus hispanica</em></td>
<td>780</td>
<td>640 ± 4 805 ± 4</td>
<td>275 ± 5 369 ± 9</td>
<td>3200 ± 100 2070 ± 100</td>
<td>57.1 + 26.2i 110.6 + 34.2i</td>
<td>2.2</td>
</tr>
<tr>
<td><em>Vitis vinifera</em></td>
<td>860</td>
<td>659 ± 4</td>
<td>341 ± 9 991 ± 50</td>
<td>98.0 + 16.1i</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td><em>Epipremnum aureum</em></td>
<td>890</td>
<td>264 ± 4</td>
<td>194 ± 9 590 ± 10</td>
<td>33.0 + 4.6i</td>
<td>1.75</td>
<td></td>
</tr>
</tbody>
</table>

Available data:
Parenchyma cells: 8-12 MPa
Aerenchyma and collenchyma cells: 2-22 MPa
Querqus leaves: 50-200 MPa.

\[ a = a_0 (f/f_{res})^n \]

n = 2, classical viscoelasticity

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II. Through transmission:
Normal incidence.
Layered approach.
Effective properties of every layer.
Leaf thickness resonances. Layered tissue approach.

Upper epidermis
Pallisade parenchyma
Spongy mesophyll
Lower epidermis

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Leaf thickness resonances. Layered tissue approach
Glossy privet leaves, 680 and 430 μm thick.

Upper epidermis
Pallisade parenchyma
Spongy mesophyll
Lower epidermis

Ligustrum Lucidium II

V = 347 m/s  
ρ = 1047 kg/m3  
α = 241 Np/m  
n = 1.8

V = 240 m/s  
ρ = 860 kg/m3  
α = 790 Np/m  
n = 1.4

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Leaf thickness resonances. Layered tissue approach.

Dicot.

Monocot.

Epipremnum aureum

Phormium tenax

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Leaf thickness resonances. Layered tissue approach.

<table>
<thead>
<tr>
<th>Species</th>
<th>V (m/s)</th>
<th>Young’s mod (MPa)</th>
<th>Young’s mod. cell wall (GPa.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PP</td>
<td>PP</td>
<td>SM</td>
</tr>
<tr>
<td>Hedera Helix</td>
<td>492</td>
<td>199,6</td>
<td>14,3</td>
</tr>
<tr>
<td>Ligustrum Lucidum</td>
<td>324</td>
<td>91,9</td>
<td>10,7</td>
</tr>
<tr>
<td>Viburnum Tinus</td>
<td>452</td>
<td>205,2</td>
<td>10,5</td>
</tr>
<tr>
<td>Magnolia Grandiflora</td>
<td>468</td>
<td>196,7</td>
<td>58,2</td>
</tr>
<tr>
<td>Epipremnum aureum</td>
<td>500</td>
<td>192,6</td>
<td>29,1</td>
</tr>
<tr>
<td>Nicotina tabacum</td>
<td>95</td>
<td>6,5</td>
<td>2,2</td>
</tr>
<tr>
<td>Vitis vinifera</td>
<td>380</td>
<td>138,8</td>
<td>37,1</td>
</tr>
<tr>
<td>Syringa Vulgaris</td>
<td>400</td>
<td>108,1</td>
<td>8,6</td>
</tr>
<tr>
<td>Prunus laurocerasus</td>
<td>420</td>
<td>120,7</td>
<td>25,2</td>
</tr>
</tbody>
</table>

Palisade parenchyma

Spongy mesophyl

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III. Through transmission:
Oblique incidence
Layered approach
Shear properties.
Through transmission, oblique incidence.
Generation of shear waves: Modulus of rigidity and Poisson’s ratio

Transmitter transducer

Leaf

Receiver transducer

100-400V
+59 dB
Pulser Receiver Sync.

Scope

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Through transmission, oblique incidence.

Generation of shear waves: Modulus of rigidity and Poisson’s ratio

<table>
<thead>
<tr>
<th>Species</th>
<th>Layer</th>
<th>$C_{33}$ (MPa)</th>
<th>Shear Modulus (MPa)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Vitis vinifera</em></td>
<td>Palisade parenchyma</td>
<td>186 + 38.6i</td>
<td>55.7 + 9.9i</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Spongy mesophyl</td>
<td>69.1 + 9.5i</td>
<td>12.1 + 1.2i</td>
<td>2.0</td>
</tr>
<tr>
<td><em>Epipremnum aureum</em></td>
<td>Palisade parenchyma</td>
<td>192.6 + 45.5i</td>
<td>48.1 + 11.6i</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Spongy mesophyl</td>
<td>13.5 + 1.4i</td>
<td>34.1 + 3.6i</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Poison’s ratio: 0.33-0.34

Shear Modulus, available data: 2-22 MPa
Poisson’s ratio, available data: 0.28 lignin, 0.18-0.4 onion epidermis, 0.23-0.5 parenchyma tissues

IV. Guided waves:
Properties of sclerenchyma fibers
Ultrasonic guided waves in sclerenchyma fibers.

*Phormium tenax* (flax, New Zealand flax)
Ultrasonic guided waves in sclerenchyma fibers.

Previous results, different techniques

J. L. Vincent et al. (1996)

- Mechanical test
  \[ E_{\text{leaf-long}} = 3.98 \pm 0.7 \text{ GPa} \]
  \[ E_{\text{fibre}} = 31.4 \text{ GPa} \]
  \[ E_{\text{cell-wall}} = 71.4 \text{ GPa} \]

- Shock waves (5 kHz)
  \[ v = 2354 \pm 191 \text{ m/s} \]
  \[ E_{\text{leaf-long}} = 4.1 \pm 0.7 \text{ GPa} \]

Ultrasonic guided waves (250 kHz)

\[ v = 2250 \pm 170 \text{ m/s} \]
\[ E_{\text{leaf-long}} = 3.76 \pm 0.7 \text{ GPa} \]
### Summary

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Cells features.</th>
<th>Tissue</th>
<th>Cell wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>us velocity (Long. / Shear)</td>
<td>E. Modulus (Young/Shear)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(m/s)</td>
<td>(MPa)</td>
</tr>
<tr>
<td>Palisade parenchyma.</td>
<td></td>
<td>300 – 500</td>
<td>95 – 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 – 245</td>
<td>12 - 60</td>
</tr>
<tr>
<td>Spongy mesophyll.</td>
<td></td>
<td>125 – 390</td>
<td>10 – 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 – 130</td>
<td>3.0 - 15</td>
</tr>
<tr>
<td>Sclerenchyma fibres.</td>
<td></td>
<td>1950-2500</td>
<td>2800 - 4600</td>
</tr>
</tbody>
</table>

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APPLICATIONS AND FUTURE WORK

Determination of water content or turgor pressure in vegetal tissues
Watering control in wineyards.

Study of structure properties relationships:
Development of biomimetic structural or functional composites

Determination of biomass content.

Monitoring of plant growth, plant response to stimuli.

Determination of the elastic properties of vegetal fibres.
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Thank you

Q & A