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Ultrasonic evaluation of the hydration degree of the orange peel

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ABSTRACT

The elastic parameters of fruit and vegetables are normally monitored in quality control processes as there is a good correlation to the degrees of firmness, turgidity and humidity. These parameters have been traditionally measured by means of penetration tests, which are destructive. This has resulted in the increased attention recently given to ultrasonic techniques applied to the quality evaluation of horticultural commodities. Nevertheless, since most of the fruit and vegetables display a viscoelastic behavior, the penetration test should be considered to be quasi-static, especially when compared with the speeds associated with the ultrasonic tests. Both methods should provide different values for the elastic parameters. The aim of this work is to study this discrepancy in the values of the elastic parameters and interpret the elastodynamic behavior of the vegetable tissue under an ultrasound test. Thus, the paper presents an ultrasonic nondestructive method to evaluate the elastic parameters of the sweet orange peel at 40 kHz. The complete dehydration process of two sets of oranges (Navelina and Ortanique) was monitored for 2 months. A linear elastic solid model with viscous losses was numerically solved using a simulation scheme based on a 3D-Spherical FDTD method (Finite-Difference Time-Domain) in order to interpret the results, which proved that the elastic parameters obtained by penetration and ultrasonic tests differ. The method provides an empirical relation between the hydration state and the elastic parameters of the orange peel. Therefore, the proposed ultrasonic test reported in this work is capable of determining the hydration state of the orange simply by measuring the propagation speed of the Rayleigh waves on the orange peel, and hence, can be used as a fruit quality index during postharvest processes.

1. Introduction

In the context of modern agriculture and its competitive markets there is growing interest regarding the need to evaluate the quality of fruit and vegetables. Quality is a subjective term consisting of many properties or characteristics such as sensory properties (appearance, texture, taste or smell) that have to be examined by people, and mechanical and functional properties, in addition to nutritive values, chemical constituents, and the absence of defects. Mindful of this, instrumentation and methods to measure quality-related attributes have been developed over the last 80 years, most recently in an attempt to establish non-destructive and real-time systems. In order to evaluate texture attributes, the mechanical properties are usually measured (Abbot, 1999). The traditional methods for evaluating these properties (such as Young's Modulus, and also the rupture force and bioyield force) are puncture or compression tests made at relatively low probe speeds ($\ll$1 m/s), typical of such instruments as the Magness–Taylor fruit firmness tester and the electronic universal (Force/Deformation) testing instruments, which are quasi-static. Acoustic methods are also used for quality evaluation (accounting for approximately 20% of the nondestructive techniques, Butz et al., 2005). In specifically, ultrasonic devices and measuring techniques have been developed over the last two decades to evaluate the mechanical properties of tissue, allowing the nondestructive monitoring of some physiochemical, biochemical and mechanical changes that occur in fruit tissues during the various stages of their pre- and postharvest existence. Some examples of these can be found in Mizrach (2000), Flitsanov et al. (2000), Verlinden et al. (2004), Bechar et al. (2005) and Gaete-Garreton et al. (2005). A review of the different ultrasonic techniques used for determining the material properties of fresh fruit and vegetable tissues during the last two decades can be found in Mizrach, 2008. Some of these techniques have been used in the past to find correlations between ultrasonic velocity and absorption through the orange peel and turgidity and the hydration state of oranges (Camarena and Martinez-Mora, 2006; Camarena et al., 2007). These techniques can also be used to evaluate the elastic parameters of the orange peel and consequently the hydration degree, as it will be demonstrated in this work.

The information of changes in postharvest physico-mechanical properties (elastic parameters) of the orange peel and the fruit under ambient and refrigerated storage conditions is important to help to determine the appropriate handling, packaging, storage and transportation systems (Singh and Sreenivasula, 2006).

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Table 1
Quasi-static measured elastic properties, calculated longitudinal (c_{bulk}) and shear (c_{shear}) wave speed, and ultrasonic measured speed of various fruits and vegetables.

Fruits	Quasi-static measured parameters			Calculated speed		Measured speed (Krautkramer and Krautkramer, 1990)
	Density ρ (kg/m^3)	Young Modulus E (MPa)	Poisson's ratio ν	c_{bulk} (m/s)	c_{shear} (m/s)	c (m/s)
Orange (Singh and Sreenivasula, 2006)	903	1.57	0.34	82.7	54.6	130–240
Avocado (Baryeh, 2000)	963	0.48	0.33	32.1	18.2	150–400
Apple (Grotte et al., 2002)	1003	3.33	0.17	65.1	36.5	98–183
Potato (Jindal and Techasena, 1985)	1087	7.14	0.25	60.8	34.1	686.9
Carrot (Bunyaphlanan, 1973)	1021	6.96	0.30	104.1	64.1	341–500

List of symbols used.

Symbol	Magnitude	Symbol	Magnitude
$\boldsymbol{\tau}$	Stress tensor	$\boldsymbol{v}$	Particle velocity vector
λ	Lame's 1st parameter	μ	Lame's 2nd parameter
E	Young modulus	ν	Poisson's ratio
Dh	Dehydration	ρ	Bulk density
f	Frequency	r	Radial coordinate
θ	Azimuth angle coordinate	φ	Elevation angle coordinate
c	Propagation speed (measured)	c_P	Pressure wave propagation speed
c_R	Rayleigh wave propagation speed	c_S	Shear wave propagation speed
η_P	Resistance coefficient longitudinal wave	η_S	Resistance coefficient shear wave
N_λ	Discrete elements per wavelength	λ_L	Longitudinal wavelength
Δt	Numerical time step	Δr	Radial element length
$\Delta\theta$	Azimuth angle element length	$\Delta\varphi$	Elevation angle element length
α_{max}	PML scaling factor	Ω_{max}	PML attenuation factor

The orange, just as most of the other juicy fruits such as the tomato, cherry and various berry fruits, exhibits viscoelastic behavior. This signifies that the elastic parameters depend not only on the force and deformation, but also on the time factor (Abbot, 1999). Regarding this, the elastic parameters obtained with quasi-static techniques may differ from those obtained using ultrasonic techniques. Evidence can be seen in Table 1 that displays a review of the elastic parameters measured by means of quasi-static procedures for different fruits, the bulk and shear speed calculated from these parameters and the speed evaluated from ultrasonic experiments. These experiments can be destructive, if inner parts of the fruit are directly measured, or non destructive, if the ultrasonic wave is excited and detected in the surface of the fruit. However, the speed measurements are always associated to shear or surface waves, as it will be demonstrated in this work. There is a clear disagreement between the calculated and measured speeds for all the fruits, and it is one of the objectives of this work to clarify this disagreement.

In this work an ultrasonic nondestructive method is proposed to evaluate the elastic parameters of the orange fruit. Two sets of oranges, Navelina and Ortanique, have been monitored ultrasonically during the entire dehydration process (2 months). From an elastodynamic point of view, the entire orange has been discomposed into three spherical shells corresponding anatomically to the flavedo (fruit peel), albedo and inner carpels tissue of the orange fruit. A linear elastic model has been proposed and a computational method based on FDTD (Finite-Differences Time-Domain) scheme has been implemented in order to simulate the propagation of the ultrasonic waves through these three layers. It has allowed us to clarify the nature of the different waves traveling through the orange, to demonstrate that the waves measured by our device are surface waves and also that the quasi-static parameters are incoherent with the ultrasonic framework.

2. Experimental set-up and measurement procedure

An experimental transmitter-receiver device was designed to excite and detect acoustic waves on the surface of the orange as can be observed in Fig. 1. A harmonic wave function generator (Agilent model 33220A, Agilent Technologies Canada, Mississauga, ON, USA) and a power amplifier (ENI model 240L, ENI, Rochester, NY, USA) were used to excite a 40 kHz ultrasonic sandwich transducer built in our laboratory. An identical transducer was used for reception, and an oscilloscope for data acquisition and analysis. Two aluminum ultrasonic energy concentrators were used to match the surface diameters of the transducers, i.e., 14 mm, to the desired area of contact with the fruit, a diameter of 2.1 mm, using conical reduction and a flat tip shape.

The transducers were mounted on a goniometer in order to change the angle between their axis, thereby changing the gap between the transducer tips (between 2 and 10 mm) and permitting a perpendicular contact between the concentrators and the orange peel. A system of springs at the bottom of the transducers controlled the contact force applied to the fruit peel, which was maintained constant at 2 N. This particular force was chosen in trial and error tests as compromised between sufficient contacts force and preventing of tip penetration into the fruit tissue.

Emitted waves penetrated the peel and propagated through the adjacent tissue along the gap between the probe tips. Wave speed was calculated by measuring the time of flight at different gaps (2, 4, 6 and 8 mm) and fitting a line. The attenuation coefficient was calculated by looking at the exponential decay of the received wave amplitude at the same gap distances (Krautkramer and Krautkramer, 1990).

On 30 January 2010, two batches of oranges were harvested from the same field (La Safor, Valencia, Spain): a set of seven Navelina sweet oranges (*Citrus sinensis*, L. Osbeck) with a similar size (mean diameter 7.1 cm and S.D. 0.3 cm), weight (mean weight 191 g and S.D. 26 g) and maturity, and a set of seven Ortanique oranges, a hybrid of the tangerine and sweet orange (*Citrus sinensis* × *Citrus reticulata*) also of a similar size (mean diameter 6.7 cm and S.D. 0.2 cm), weight (mean weight 130 g and S.D. 13 g) and maturity. No specific chemical processing was applied to the fruit and it was stored under ambient conditions (20–23 °C and 49–53% relative humidity).

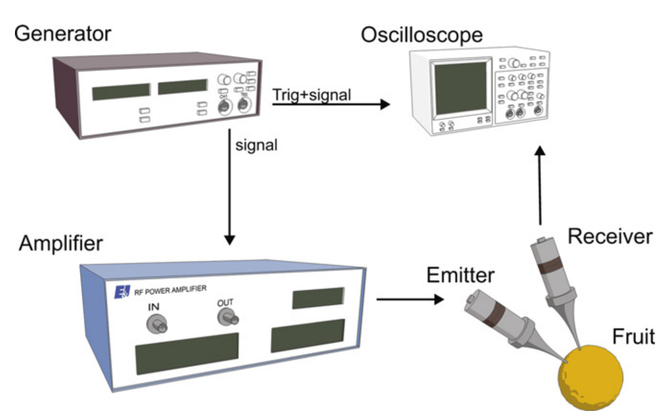

Fig. 1. Diagram of the ultrasonic measuring system.