Journal of Food Engineering 147 (2015) 49–55

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Ultrasonic determination of mechanical properties of meat products

Konrad W. Nowak [a,*], Marek Markowski [a], Tomasz Daszkiewicz [b]

[a] Department of Systems Engineering, Faculty of Engineering, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Oczapowskiego 2, Poland
[b] Department of Commodity Science and Animal Raw Material Processing, Faculty of Animal Bioengineering, University of Warmia and Mazury in Olsztyn, 10-719 Olsztyn, Oczapowskiego 2, Poland

ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form 25 August 2014
Accepted 10 September 2014
Available online 28 September 2014

Keywords:
Meat products
Mechanical properties
Ultrasound
Poisson's ratio
Young's modulus

ABSTRACT

Young's modulus and Poisson's ratio values were determined for selected pork coldcuts (canned ham and Podwawelska sausage) based on measurements of sound velocity and the attenuation coefficient in samples, the results of compression tests and sample density measurements. All measurements were performed at 5 °C and 20 ± 1 °C. Poisson's ratio for the analyzed products was determined at the indicated temperature based on the measured acoustic parameters, sample density and the value of Young's modulus calculated in mechanical tests. The average value of Poisson's ratio was determined 0.49999, and it was similar to the values cited by other authors. The average Poisson's ratio and the results of ultrasonic measurements were used to calculate Young's modulus. At 5 °C, the average Young's modulus values for canned ham and Podwawelska sausage were determined at 185.3 and 148.2 kPa, respectively, in the compression test, and at 193.1 and 145.4 kPa, respectively, in ultrasonic measurements. At 20 °C, the above values were determined at 151.4 and 99.9 kPa, and at 147.2 and 86.1 kPa, respectively. Young's modulus values calculated based on acoustic measurements did not differ significantly from the values determined based on the results of mechanical tests.

1. Introduction

The quality of meat and meat products is largely determined by the rheological properties of raw materials, in particular texture. Texture incorporates various properties that determine tenderness, a sensory attribute of meat that is most highly valued by the consumers (Bekhit et al., 2014; Boleman et al., 1997). In practice, product tenderness is predicted based on the results of mechanical tests.

Meat is a non-homogeneous and anisotropic material, and the properties of its structural elements are not always consistent with the overall mechanical properties of tissues (Lepetit and Culioli, 1994). Meat products, including coarse-ground and medium-ground sausage and meat blocks, contain many additives, such as emulsifiers, preservatives, spices, fat and plant materials that differ in their physicochemical properties. The non-homogeneous character of such mixtures poses one of the greatest problems in determinations of the sensory attributes of meat products. Products that combine ingredients representing various fractions, including fractions with anisotropic particles (meat), can be regarded as isotropic materials because on the macro scale, their properties are identical regardless of the direction of measurement (Lu and Chen, 1998). If a material sample is sufficiently large, i.e. if its smallest dimension, such as the diameter, is significantly larger than the dimensions of the largest particle of the mixture that makes up the sample, it can be regarded as a homogeneous sample with effective physicochemical properties averaged for the bulk of the sample. This approach is used to determine the mechanical properties of solid foods, including meat products (Del Nobile et al., 2007; Yilmaz et al., 2012).

The majority of food products, including meat and meat products, demonstrate both elastic and viscous properties in mechanical tests. Until recently, the mechanical properties of meat products were determined mainly by destructive methods with the use of Maxwell and Burgers models (Andrés et al., 2008; Bruno and Moresi, 2004; Campus et al., 2010; Chattong and Apichartsrangkoon, 2009; Dolz et al., 2008; Karaman et al., 2011; Kuo et al., 2000; Myhan et al., 2012). The use of mechanical tests in determinations of the rheological properties of meat products requires time-consuming measurements. Rapid non-destructive methods, such as vision inspection, magnetic resonance imaging and ultrasonic measurements, pose an effective alternative to the above.

The use of rapid, non-destructive methods in analyses of the mechanical properties of food products, including Young's

* Corresponding author. Tel.: +48 89 523 4940; fax: +48 89 523 4469.
E-mail address: konrad.nowak@uwm.edu.pl (K.W. Nowak).

http://dx.doi.org/10.1016/j.jfoodeng.2014.09.024
0260-8774/

Notation

A	amplitude of registered ultrasonic signal, mV
a	coordinate describing the state of equilibrium, m
d	sample thickness, m
E_c	Young's modulus determined based on the results of the compression test, Pa
E_u	Young's modulus determined based on ultrasonic measurements, Pa
K	bulk modulus: $K = (\beta_{ad})^{-1}$, Pa
m_A, m_W	sample weight measured in air and water, respectively, kg
r	retardation coefficient, s
t	temperature, °C
T	dynamic stress, Pa
x	coordinate describing the direction of wave propagation, m

Greek symbols

α	acoustic attenuation coefficient, m^{-1}
β_{ad}	adiabatic bulk modulus, Pa^{-1}
η_1, η_2	shear viscosity, volume viscosity, kg m^{-1} s^{-1}
μ	Lamè constant, Pa
λ	Lamè constant, Pa
ξ	displacement relative to equilibrium state, m
ρ	density of a laminar medium, kg m^{-3}
τ	time, μs
ν	Poisson's ratio
ω	wave frequency, Hz

modulus and Poisson's ratio, continues to attract the interest of researchers and food producers. Tao and Peng (2014) used hyperspectral imaging techniques in an analysis of meat tenderness. Low intensity ultrasound is one of the most frequently investigated method (Kundu, 2004; Lepetit and Culioli, 1994; Llull et al., 2002a, b; McClements and Gunasekaran, 1997). The majority of studies analyzing the above technique focused only on the correlations between the results of mechanical tests of biological materials and acoustic parameters describing those materials (Ayadi et al., 2007; Nielsen et al.,1998). Some authors relied on mathematical formulas relating to the propagation of acoustic waves through an elastic medium (Ross et al., 2006). In the latter method, elastic strain resulting from external force applied to a material can be determined based on Lamè constants, λ and μ, which can also be expressed in terms of Young's modulus and Poisson's ratio (Kundu, 2004; Righetti et al., 2003). Selected studies incorporated both approaches to analyze the mechanical properties of food products (Llull et al., 2002a, b). Chen et al. (1996) and Glozman and Azhari (2010) investigated the correlations between the acoustic and mechanical properties of soft biological materials by relying on the theory of acoustic wave propagation in an elastic continuous medium.

Recent years have witnessed the emergence of two research methods: magnetic resonance elastography (MRE), which is based on magnetic resonance imaging (MRI) and tracks mechanical wave propagation in a product, and transient supersonic shearwave propagation (SWP) (Bercoff et al., 2004; Damez and Clerjon, 2013; Gruwel et al., 2010; Sapin-de Brosses et al., 2010). Both techniques support non-destructive determination of the viscoelastic properties of soft tissues, and they are applied mainly in medical diagnosis. MRE and SWP are also used to analyze the mechanical properties of food products, including meat (Budelli et al., 2014; Gruwel et al., 2010; Sapin-de Brosses et al., 2010). The discussed methods are relatively expensive – they require highly qualified personnel, specialist equipment and software.

A different, simplified approach often used in practice is based on the assumption that the attenuation of sound waves traveling through meat and meat products is negligibly small. In such a case, the propagation of acoustic waves in a material can be described with sufficient accuracy based on the theory of elastic and lossless continuous media. In such media, sound waves are propagated without the loss of mechanical energy. Several studies (Bamber and Hill, 1979; Chivers and Parry, 1978; Nowak and Markowski, 2013) have demonstrated that meat and meat products attenuate sound waves, therefore, they should be regarded as lossy media where energy is significantly dissipated and acoustic waves are attenuated. The above considerations point to the need for a simplified method of estimating the mechanical properties of meat and meat products based on non-destructive acoustic techniques and the theory of acoustic wave propagation in viscoelastic lossy media.

The objective of this study was to estimate Young's modulus and Poisson's ratio of selected meat products based on ultrasonic measurements and the theory of acoustic wave propagation in a lossy medium. The correlations between ultrasonic (sound velocity and attenuation coefficient) and mechanical parameters (Young's modulus and Poisson's ratio) of a material were analyzed. The advantage of this approach is that it takes into account not only the elastic, but also the viscous properties of meat products, which is rarely observed in other published studies (Chen et al.,1996; Llull et al., 2002a, b; Ross et al., 2006; Glozman and Azhari 2010). The mechanical parameters of the tested materials were described theoretically based on ultrasonic measurements, and Poisson's ratio was calculated for selected meat products based on the results of acoustic and mechanical tests. Poisson's ratio and ultrasonic measurements describing one batch of meat products were used to calculate Young's modulus for the second batch of the same products. The obtained values were compared with the results of mechanical tests performed on the same batch of products.

2. Materials and methods

2.1. Theory

The movement of an acoustic particle in a flat longitudinal wave propagating in a viscoelastic medium in the direction of the x axis can be described with the use of the below formula (Landau and Lifshitz, 1986):

$$\rho \frac{\partial^2 \xi}{\partial \tau^2} = \frac{\partial T}{\partial x} \tag{1}$$

where the correlation between coordinate a, which describes the equilibrium state of the acoustic particle, particle displacement ξ from the state of equilibrium and the particle's current location described by coordinate x is given by the following Eq. (2):

$$x = a + \xi \tag{2}$$

It has been assumed that stress at any point of a viscoelastic medium is the sum of elastic and viscous stress (Landau and Lifshitz, 1986). The displacement of points in the analyzed medium caused by the propagation of low-amplitude sound waves in the direction