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A critical review of the acoustic resonance approach in food processing: A novel non-destructive technology

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Abstract
Food storage conditions influence the subsequent softening process and shelf life. In reference texture tests, quality parameters have traditionally been measured using a texture analyzer or penetrometer. Acoustic Vibration Technology (AVT) was used in this study to estimate quality parameters of food products in a non-destructive manner. Using a shaker, this technique was used to detect responses to imposed vibration of intact food material. To process response signals, a fast Fourier transform algorithm was used, and the desired results were extracted. This study demonstrates the AVT's and vibration response data's ability to predict quality and the significant advantage for commercial scale equipments.

Keywords: Acoustic vibration, quality and non-destructive technique

1. Introduction
The quality of a product is related to both internal variables (firmness, sugar content, acid content, and internal defects) and external variables (shape, size, external defects, and damage). The growing consumer demand for high-quality products has resulted in the development of novel quality assessment technologies such as optical, acoustic, and mechanical sensors. Currently, these quality variables are evaluated using a destructive method that disturbs the entire product sample. Because of the use of a destructive method of quality assessment, the product may lose some of its attributes prior to analysing its attributes. Such a procedure necessitates a great deal of chemical analysis, calculations, and is extremely time consuming. However, in order to retain its inherent properties, processors must measure these quality variables in a non-destructive manner. This problem initiates the researchers and manufacturers to develop non destructive techniques.

Consumers are increasingly focusing on the quality of agricultural products when making purchasing decisions; thus, evaluating the quality of agricultural products is important not only for farmers but also for food processors and distributors. Quality evaluation considers a variety of factors, including appearance, taste, and fragrance, of which texture is an important attribute. Hardness, crispness, juiciness, and mealiness are all desirable textures (Mitsuru and Naoki, 2010) [19].

The texture of an edible material is defined by the British Standards Institution as the attribute of a substance resulting from a combination of physical properties perceived by the senses of touch (including kin aesthesis and mouth feel), sight, and hearing (Anonymous, 1975) [2]. Fruit firmness is an important quality variable; it is an indirect measurement of ripeness, and its accurate assessment allows for the establishment of appropriate storage periods and optimum transport conditions (Garca *et al*., 2005). Firmness, along with sugar and acid content determination, are important parameters used in the objective evaluation of fruit and vegetable quality. Firmness is probably the most subjective of these three, because the relatively simple output of a probe on fruit surfaces is used to interpret complex rheological behaviour (Muramatsu *et al*., 1997) [23]. In the majority of quality evaluations, representative samples were chosen and evaluated for maturity and texture control before the product was discarded. The limited sampling does not account for the total variation in maturity at harvest and makes monitoring subsequent changes that may occur during storage difficult (Falk *et al*., 1958) [8].

Furthermore, there is no external evidence reflected by colour in the specific evaluation of kiwifruit that would facilitate the assessment of uniformity within bulk shipments (Muramatsu *et al*., 1997) [23]. As a result, an additional comprehensive non-destructive method for product evaluation would provide significant benefits for quality control. Falk *et al*., 1958 [8]; Finney 1970; Yamamoto and Haginuma, 1984a, b, c [35-37]; and Abbott 1994 [1] all reported non-destructive firmness measurement methods for various food products. Non-destructive devices capable of measuring product internal variables have grown in popularity as a result of technological advances over the last few decades, such as image processing, visible and infrared light inspection, acoustic vibration technique, NMR technique, and mechanical simulation. Originally designed for use in the laboratory, these have been adapted for online use. This article describes in detail the methodology, components, operating principle, and applications of the acoustic vibration technique for measuring or assessing the quality of food products.

2. Methodology

2.1 Non-destructive quality assessment

Various methods based on deformation force are used to evaluate the texture of agricultural products (e.g., the puncture test and compression test). Because these methods are destructive, the quality evaluation of agricultural products is supposed to be a sample inspection. One hundred percent inspection is preferred for better quality control of agricultural products; thus, nondestructive evaluation methods are in high demand. As a result, there are several nondestructive methods for evaluating the quality of agricultural products that are widely used or in development.

2.2 Deformation technique

Nondestructive deformation methods can be used as long as the deformation is small enough not to harm an agricultural product. Hertz's theory contains the fundamental principle governing the measurement of force – deformation; the compressive stress between two bodies in contact is proportional to their elastic modulus and inversely proportional to their radius. One of the bodies is a fruit, and the other is a metallic plunger (either a small sphere or flat-ended probe). The non-destructive force-deformation curve can be recorded using an analogue or a piezoelectric sensor positioned at the back of the compression plunger by applying a small deformation force to the fruit that causes no damage. The curve is produced by applying a small load for a fixed period of time (Macnish *et al.*, 1997) [17] or by calculating the force necessary to reach a pre-set deformation (Fekete and Felföldi, 2000) [9].

2.3 Acoustic vibration technique

When an acoustic wave strikes a food product, the reflected or transmitted acoustic wave is determined by the product's characteristics. Acoustic technology is frequently used to estimate product firmness, in addition to other quality parameters (Maristella and Marina, 2012) [18]. The acoustic firmness index is based on the relationship between the modulus of elasticity and the fruit's resonant frequencies of vibration.

The acoustic vibration technique is further classified based on vibration detection sensors and excitation methods (Figure 1). Sensors are classified into two types: contact sensors and noncontact sensors. Contact sensors are attached directly to the surface of the sample being examined. Acceleration pickups and piezoelectric sensors are two examples of commonly used sensors. Microphones and optical sensors such as laser Doppler vibrometers (LDVs) and laser interferometers are examples of noncontact sensors. Noncontact sensors have the advantage of being completely non-destructive and exerting no physical or mechanical influence; thus, they do not damage the surface of a sample.

The acoustic response technique for measuring fruit firmness has been studied with two different approaches: involving values within the audible spectrum (sonic) or using ultrasound (Maristella and Marina, 2012) [18]. According to Subedi and Walsh (2009) [28], the sound velocity of the vibration produced by the fruit hit by a plastic plunger, detected by two unidirectional microphones, was demonstrated to non-destructively assess the ripening stage of banana, mango and peach fruits, although it does not measure the same property as the penetrometer whereas the vibrational response of pear (Terasaki *et al.*, 2006; Taniwaki *et al.*, 2009a) [32, 29], melon [Taniwaki *et al.*, 2009b; Taniwaki *et al.*,2010c] [30-31] and persimmon fruits was sensed by means of a laser Doppler vibrometer and an acceleration pickup and the Elasticity Index, determined by using both signals, highly correlated with the results of a sensory test. The authors concluded that this technique can be useful for predicting the optimum ripeness for edibility of these fruits but that the difference in texture attributes is explainable only in part by the frequency bands.

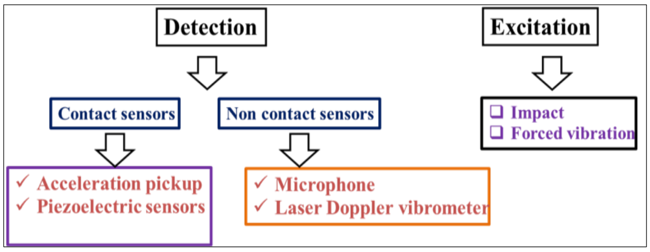

Fig 1: Classification of Acoustic vibration technique

There are several types of vibrations that can be used, the most common of which are acoustic and mechanical (which in some cases are very similar). Acoustic methods measure the signal (audible range: about 0 – 20,000 Hz) issued by the fruit after making it vibrate with a small impact using a microphone or a piezoelectric sensor. The captured acoustic signal is Fourier transformed, and the main frequency is calculated. Green fruit has a pressure range of 5 MPa, while overripe fruit has a pressure range of 0.5 MPa (Studman, 1999) [27].

2.4 Acoustic vibration equipment components

The experimental setup consists primarily of a platform on which the sample was placed. Sensitive sensors (contact or non-contact) such as microphones, piezoelectric sensors, Laser Doppler vibrometers, or other sensors were attached to the product or used in other indirect ways to detect vibration or frequency after applying a small force to the product. The force required to generate the vibration can be applied using a pendulum arrangement made up of either a ball or a small probe. The product's quality parameters can then be determined by analysing the frequency or vibration with a Fast Fourier Transformation (FFT) analyzer. Typical experimental setup of Acoustic vibration equipment consisting all its components was shown in the Figure 2. Then the frequency 'f' of the model is given by;

$$f = \frac{1}{2\pi}\sqrt{\frac{4k}{m}} \quad \text{and} \quad k = \pi^2 f^2 m$$

Where 'k' is the spring constant of the system and 'm' is the mass of the sample.

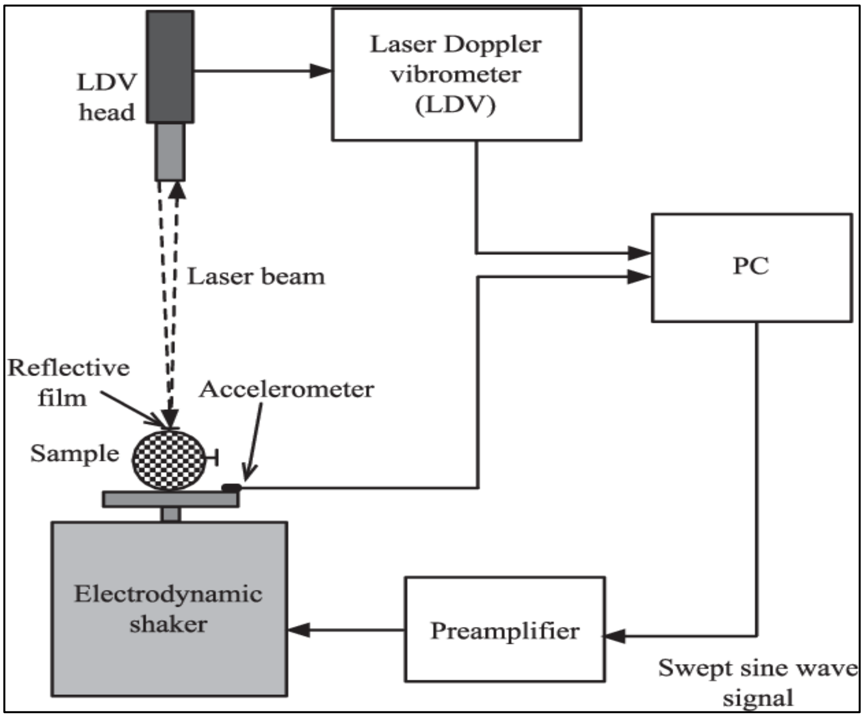

Fig 2: Experimental setup for excitation by impact and detection by piezoelectric sensor based acoustic vibration technique

2.5 Applications of the acoustic vibration technique in quality

In order to assess the quality and maturity indices of fruits and vegetables, various parameters were considered which are tabulated in Table 1. Destructive methods can only be used on a small number of samples and are thus not always representative of the entire sample. Using as few samples as possible frequently results in increased lot to lot variability in the parameter measured. Even when picked fruits conform to the harvest parameters on average, there is always variability at harvest.

Table 1: In order to assess the quality and maturity indices of fruits and vegetables, various parameters were considered which are tabulated

Sl. No	Index	Method of Determination	Examples
1.	Elapsed days from full bloom to harvest	Computation	Apples, pears
2.	Mean heat units during development	Computation from weather data	Apple
3.	Development of abscission layer	Visual or force of separation	Some melons, apples, feijoas
4.	Surface morphology and structure	Visual	Cuticle formation on grapes, tomatoes; netting of some melons; gloss of some fruits (development of wax)
5.	Size	Various measuring device, weight	All fruits
6.	Specific gravity	Density gradient solution; flotation techniques; volume/weight	Cherries, watermelons
7.	Shape	Dimensions; ratio charts	Angularity of banana finger; full cheeks of mangoes
8.	Firmness	Firmness tester, deformation	Apples, pears, stone fruits
9.	External colour	Light reflectance, visual colour charts	All fruits
10.	Internal colour and structure	Light transmittance, delayed light emission, visual examination	Flesh colour of some fruits
	Compositional Factors		
11.	Total solids	Dry weight	Avocados, kiwifruit
12.	Starch content	KI test, other chemical tests	Apples, pears
13.	Sugar content	Hand refractometer, chemical tests	Apples, pears, stone fruits, grapes
14.	Acid content, sugar/acid ratio	Titration, chemical tests	Pomegranates, citrus, papaya, kiwifruit
15.	Juice content	Extraction	Citrus fruits
16.	Oil content	Extraction, chemical tests	Avocados
17.	Astringency (tannin content)	Ferric chloride test	Persimmons, dates
18.	Internal ethylene concentration	Gas chromatography	Apples, pears

Non-destructive methods, on the other hand, can be applied to a large number, if not all, of fruits, and non-destructive analyses can be repeated on the same samples, monitoring physiological changes (Nicola *et al*., 2007).

There have been several reviews published on non-invasive technologies for fruit and quality sensing, including visible (VIS) and near infrared (NIR) spectroscopy, multi- and hyper-spectral imaging, time- and space-resolved reflectance spectroscopy, computer vision, nuclear magnetic resonance (NMR) and magnetic resonant imaging (MRI), acoustic methods, and wireless sensing (Ruiz-Altisent *et al*., 2010) [26]. This review focuses on spectral maturity indices and nondestructive mechanical techniques developed in recent years for assessing fruit ripening. Table 2 shows the methods and parameters used for non-destructive evaluation of various fruits and vegetables.

Table 2: Methods and parameters used for non-destructive evaluation of different products

Crop	Method	Parameters used	Reference
Apple	Acoustic, VIS-NIR spectroscopy	Acoustic resonance frequency, fruit absorbance	Zude *et al.*, 2006 [38]
Apple	Acoustic (ultrasound)	Wave velocity	Kim *et al.*, 2009 [16]
Apple	Acoustic, low mass impact, impact test, compression test, puncture test	Maximum deformation, maximum force, acoustic frequency	Molina-Delgado *et al.*, 2009 [21]
Banana, mango, peach	Acoustic	Sound velocity	Subedi *et al.*, 2009 [28]
Kiwifruit	Dynamic impact	Peak of force, pulse duration, impulse	Ragni *et al.*, 2010 [24]
Melon, persimmon, pear	Acoustic	Resonant frequency	Terasaki *et al.*, 2006 [32] Taniwaki *et al.* 2009a [29]
Orange	Acoustic (ultrasound)	Wave velocity and amplitude	Camarena *et al.*, 2006 [3], Jiménez et *et al.*, 2012 [15]
Peach	Impact and acoustic	Maximum acceleration, resonant frequency Spectrum amplitude, band magnitude	Diezma-Iglesias *et al.*, 2006 [17]
Peach	Impact	Resonance frequency	Wang et *et al.*, 2006 [34]
Peach, nectarin, plum	Hammer impact	SFI score from SIQ firmness tester	Valero *et al.*,2007 [33]
Peach	VIS spectroscopy, impact, deformation test	Force and time impact, maximum force, reflectance R680 and R450	Ruiz-Altisent *et al.*, 2006 [25]
Peach	Impact and acoustic	Resonance frequency of the first elliptical mode	Ruiz-Altisent *et al.*, 2010 [26]
Peach	VIS spectroscopy, impact	Reflectance, maximum impact acceleration, impact hardness, time for maximum acceleration, maximum deformation	Herrero-Langreo *et al.*, 2012 [13]
Pear	Ball impact	Resonant frequency	Hernandez-Gomez *et al.*, 2005 [12]
Tomato	Acoustic (ultrasound)	Wave attenuation	Mizrach, 2007 [20]
Tomato, apple	Impact and acoustic	"SIQ-FT" index (calculated by force peak amplitude and impact response).Resonant frequency	De Ketelaere *et al.*, 2006 [6]

3. Conclusion

One approach to non-destructive agricultural product evaluation is to develop devices that are more practical and cost-effective in evaluating the best quality attributes. Such devices are currently in the works. Another approach is to gain a theoretically sound understanding of agricultural product acoustic vibrations. Although there have been studies on the vibrational modes of various shapes (Cherng, 2000; Cherng and Ouyang, 2003; Jancsok *et al*., 2001) [4-5, 14], the vibrational characteristics of agricultural products with two-layered spherical shells, such as watermelons, have not been thoroughly investigated. Understanding such dynamics would aid in the development of a methodology for obtaining inner quality data on agricultural products.

Although the AVT used for quality estimation is simple, inexpensive, and yields acceptable results, non-destructive techniques do not always measure the same quality attribute as their destructive counterparts. Furthermore, the authors frequently observed poor relationships between acoustic firmness and the M-T test, and non-destructive impact measurements were found to be highly sensitive to changes in turgidity but less capable of tracking changes in ripening. Future research should concentrate on the use of multiple ND techniques at the same time. As a result, the resulting information is more complete and accurate than when a single technique is used.

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