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Nondestructive quality evaluation of agro-products using acoustic vibration methods--A review

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Abstract

Quality evaluation of agro-products is quite important because it is the basis for growers, distributers and consumers. Various novel and emerging nondestructive methods were proposed for quality evaluation of agro-products. The acoustic vibration method is one of the major nondestructive methods for agro-products in pre- and postharvest research and industrial practice. Acoustic vibration characteristics of agro-products can be used for texture evaluation, prediction of optimum eating and harvest ripeness, ripeness classification and defect detection.

Generally, there are three parts in the process of acoustic vibration method, including the excitation module, signal acquisition module and signal processing module. The impact method and forced method are two excitation methods in the excitation module, and there are contact and non-contact sensors for vibration measurement in the signal acquisition module. Non-contact measurement can meet the requirement of rapid and nondestructive measurement, especially for the on-line detection. However, increasing demand for accurate and cost-effective measurement remains a challenge in the agro-products industry. Comparison of acoustic vibration methods and traditional destructive methods was also discussed, which helps to give a more comprehensive assessment for the acoustic vibration method.

Keywords

nondestructive technique, quality evaluation, agro-products, acoustic vibrationContents

1.Introduction

Quality is a human construct comprising various characteristics. Quality of agro-products includes sensory characteristics (size, shape, texture, taste and flavor), trophic compositions, chemical compositions, mechanical characteristics, functional characteristics and defects (Abbott, 1999). Along with the development of society and economy, social demands for agro-products with good variety and internal quality become higher and higher. Customers are expecting that what he buys should be provided in best quality and service (Suphamitmongkol et al., 2013). However, traditional destructive detection methods, such as sampling inspections, are generally time-consuming, complex and costly. Therefore, the demands for high quality by consumers and lack of labour are promoting an advance in developing new approaches for various quality variables evaluation in a nondestructive way in the past few decades (Moreda et al., 2009).

Among various nondestructive techniques, the acoustic vibration method is an common and efficient way for nondestructive quality inspection of agro-products. Quality of agro-products is evaluated according to their vibration response under some kind of excitations in this method. The acoustic vibration waves include reflection, scattering, transmission and absorption when they interact with the agro-products. The form of transmission depends on the acoustic vibration characteristics of agro-products. Acoustic vibration characteristics of agro-products are related to their mechanical and structural properties. The response of agro-products to vibrations depends on their modulus of elasticity, Poisson's ratio, density, mass and shape (García-Ramos et al., 2005; Zhang et al., 2016). On a micro level, the mechanical and structural properties of agro-products are determined by the characteristics of their cells, such as cell size, cell wall thickness and strength and cell turgor pressure (Harker et al., 1997). Agro-products continue to ripen during growing period and storage (Kondo and Takano, 2000). The mechanical and structural properties of agro-products are changing along with the cell growth and metabolism. Therefore, the acoustic vibration method is widely used for evaluating qualities those are associated with mechanical and structural properties.

The objective of this article is to provide a review of development in acoustic vibration methods for nondestructive quality evaluation of agro-products, including the applications, commonly used excitation techniques and vibration measurement sensors. Staring with the basic theory of the acoustic vibration method; the review also discussed the relationships between acoustic vibration methods and traditional destructive methods for texture measurement.

2.Theory of the acoustic vibration method

Acoustic vibration characteristics of agro-products were measured in the acoustic vibration method. Internal information of agro-products can be obtained by the acoustic vibration wave interacted with tested sample. Acoustic vibration parameters include natural frequency, propagation velocity, acoustic impedance, attenuation coefficient, etc. The differences in

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mechanical and internal structures of agro-products result in different acoustic vibration characteristics (Sun et al., 2010).

As shown in Figure 1, A test sample can be assumed to be simple elastic body, which is composed of two masses connected with a spring (Taniwaki and Sakurai, 2010). The natural frequency (*f*) of the system can be calculated by equation (1).

$$f = \frac{1}{2\pi}\sqrt{\frac{4k}{m}} \qquad (1)$$

where, *m* is the sample mass, *k* is the spring constant of the system. The equation can be converted into:

$$k = \pi^2 f^2 m \qquad (2)$$

It is obviously that f^2m is proportional to *k*. Spring constant *k* is related to the elastic properties of the system (the tested sample). Therefore, f^2m can be used as an index for elasticity or texture evaluation.

Abbott et al. (1968) applied an acoustic vibration technique for measuring texture of apples. The results showed that the index, f_2^2m, can be effectively used for the measurement of apple texture. f_2^2m was called “stiffness coefficient” because it measure the stiffness or firmness of the fruit in this study. Finney (1970) also concluded that Young’s modulus and shear modulus of apples were highly correlated with f_2^2m of intact fruit. Later, Cooke et al. (Cooke, 1972; Cooke and Rand, 1973) proposed a modified stiffness coefficient, $f^2m^{2/3}$, based on a theoretical analysis of vibration modes in a three-media elastic sphere. The modified stiffness coefficient was proved to have a better correlation with the fruit texture.

It is concluded that acoustic vibration characteristics largely reflect its elasticity properties of agro-products based on the theoretical analyses and experimental results. Therefore, the acoustic vibration method can be used for internal quality evaluation of agro-products, especially for those corresponding to elasticity properties or internal structure of agro-products.

3. Applications of acoustic vibration methods in quality evaluation of agro-products

The response of agro-products to vibrations depends on their modulus of elasticity (firmness), mass, density, Poisson's ratio, shape, etc. (García-Ramos et al., 2005; Zhang et al., 2016). In addition, Existing studies showed that the Young's modulus was a key factor affecting the acoustic vibration characteristics of agro-products (Chen and De Baerdemaeker, 1993a; Lu and Abbott, 1996; Song et al., 2006). Therefore, the acoustic vibration method was mainly developed for texture evaluation of agro-products. Since texture gradually changed during storage, the acoustic vibration method was also used for ripeness classification and optimum eating ripeness determination. In addition, the defects change the structure of agro-products, and also cause the change of vibration response of agro-products. Therefore, the acoustic vibration method can be also used for defect detection of agro-products.

3.1 Texture evaluation

Texture is one of the determinant attributes used for quality evaluation of agro-products. Desired textures include firmness, stiffness, adhesiveness, springiness, chewiness and mealiness (Lawless and Heymann, 2010; Chen and Opara, 2013; Taniwaki and Sakurai, 2010). Firmness is the most commonly used index among these texture indices. Precise evaluation of texture is important for the determination of the optimum harvest time, best edible time, postharvest storage and quality grading (Zhang et al., 2014a). Most of the existing studies on agro-products quality evaluation by the acoustic vibration method are focusing on the texture evaluation.

Stiffness coefficient combined resonance frequency and mass can compensate the influence of sample size. The correlation coefficients (r) between stiffness coefficient and texture indices ranged depending on variety, storage condition, sample size and excitation method (Abbott, 1999). Good correlations (r>0.8) were obtained for many fruits, such as apples (Abbott et al., 1992), pears (Gomez et al., 2005; Zhang et al., 2015a), kiwifruits (Abbott and Massie, 1998) and pitayas (Fumuro et al., 2013). In addition, shape also has an effect on acoustic vibration characteristics (Chen and De Baerdemaeker, 1993b; Lu and Abbott, 1996; Jancsok et al., 2001). However, the influence of shape was generally ignored in existing studies for texture evaluation.

A problem for texture evaluation is that too many texture indices were used. Texture indices include firmness, stiffness, crispness, chewiness, juiciness, etc. Moreover, the destructive detection methods were different even for the same texture index because there is no standard method for texture detection. For example, the puncture test. The type of probe, penetration depth and loading speed affected the test results in the puncture test. However, few parameter settings in the puncture test were same among different researches. Therefore, the prediction results of the acoustic vibration methods obtained by different researchers lacked contrast.

3.2 Prediction of optimum eating and harvest ripeness/ ripeness classification

Agro-products generally become soft during the period of ripening and storage. Consumers demand for the best eating time so that the quality of agro-products is optimal for eating. However, agro-products are usually at different stages of ripeness no matter in the market or on the tree. Therefore, the monitor of ripening process and classification of agro-products based on their maturity help both consumers and distributers to determine the preservation method and edible time (Taniwaki et al., 2009a).

Taniwaki et al. (2009a; 2009c; 2010) applied the laser Doppler vibrometer method to predict the optimum edible time of persimmons and melons. Changes in the elasticity index (*EI*) over time were monitored to investigate the speed of ripening. For example, Figure 2 shows the changes in *EI* of melons over time measured by Taniwaki et al. (2010). The ripening speed was defined as ΔEI/day. The period of optimum ripeness was determined by the sensory evaluation. The results showed that the shelf-life and time range of optimum ripeness can be estimated through predetermined *EI*. Fumuro et al. (2013) monitored the time-course changes in *EI* of pitayas harvested at different days after anthesis. The results showed that *EI* at optimal harvest time was 6.2×10^6 and 7.3×10^6 for pollinated fruit in July and September, respectively.

Hongwiangjan et al. (2015) assessed the maturity of pomelos harvested at different months after anthesis using the acoustic vibration method. The results showed that pomelos could be separated into immature, early-mature and late-mature groups with an accuracy of 96.7%. Vursavus et al. (2015) explored the ripeness of peaches by dividing peaches into soft, intermediate and hard categories. The acoustic vibration characteristics of peaches were measured by three nondestructive acoustic sensors. The best classification result with an error rate value of 13% was obtained by the three sensors were fused. Baltazar et al. (2008) monitored the changes in stiffness coefficient of tomatoes over time. Tomatoes at different ripening stages were classified by Bayesian classification with an 11% classification error.

3.3 Defect detection

3.3.1 Eggshell cracks detection

Eggshell cracking is a thorny problem in the egg industry. Cracked eggs were vulnerable to germs infection causing health hazards during storage, such as Salmonella. Moreover, harmful microorganisms affected intact eggs around the cracked eggs. The distributers usually suffered huge economic losses because of cracked eggs. Therefore, accurate identification and removal of

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cracked eggs is quite important in the egg industry (Jindal and Sritham, 2003). The acoustic vibration method is one of the major crack detection methods.

In most existing studies, eggs were excited by the impact method, and the response signals were collected by microphones (Cho H. K. et al., 2000; De Ketelaere et al., 2000; Jindal and Sritham, 2003; Lin et al., 2009; Deng et al., 2010; Wang et al., 2016) or piezoelectric sensors (Wang and Jiang, 2005; Zhao et al., 2010). A novel eggshell crack detection device was proposed by Jin et al. (2014; 2015), shown in Figure 3. An electret microphone was attached to the back of a corrugated plate to measure response signals when eggs rolling down from the top of the plate. In addition, the combination of acoustic vibration and computer vision was developed for eggshell cracks detection by Pan et al. (2011a; 2011b). All the existing studies demonstrated that the acoustic vibration method for eggshell cracks detection is feasible.

3.3.2 Hollow heart detection

Hollow heart of agro-products is a serious quality problem most likely to occur when growing conditions alternate between wet and dry, and hot and cold temperatures (Diezma-Iglesias et al., 2004). Hollow heart usually affected the taste and shelf life of watermelons (Sun et al., 2010). The acoustic vibration response of watermelons with hollow heart is different from those with good internal quality. Therefore, various devices were designed and developed for non-destructive detection of internal hollow or creases based on the acoustic vibration method

(Stone et al., 1996; Armstrong P. R. et al., 1997; Diezma-Iglesias et al., 2004; Rao et al., 2004; Diezma Iglesias et al., 2005; Yanjun et al., 2011). Figure 4 shows a typical acoustic vibration device for watermelon hollow detection (Diezma-Iglesias et al., 2004; Diezma Iglesias et al., 2005). Besides watermelons, the acoustic vibration method was also applied for hollow heart detection of potatoes (Elbatawi, 2008).

3.3.3 Other defect detections

Kadowaki et al. (2012) detected the core rot fruit in “Kosui’ Japanese pear by a nondestructive resonant method. Fruit with f_2 less than 500 Hz had core rot of more than 5% of fruit volume. Discrimination rate was 96.9%. the results also showed that core rot segregation by the second resonance frequency (f_2) is better than that by the third resonance frequency (f_3), probably because smaller fruit with higher resonant frequency may be more resistant to the invasion of pathogens than larger fruit with lower resonant frequency.

Chen et al. (2011) proposed an impulse response method for the classification of gelled and non-gelled preserved eggs. The decay rate was measured by the peak exponential regression analysis. The results showed that gelling preserved eggs generally had a decay rate below 80, and the error rate of gelled preserved eggs identification was 7.6%.

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Muramatsu et al. (1999) applied the laser Doppler technique to detect citrus fruit afflicted with internal defects. The results showed that the phase shift of granulated fruit was significantly lower at all frequencies used in the experiments.

4.Development of acoustic vibration methods in quality evaluation of agro-products

4.1 General process of the acoustic vibration method

Figure 5 shows the general process of acoustic vibration method for quality evaluation of agro-products. Generally, there are three parts in the process, including the excitation module, signal acquisition module and signal processing module. Tested sample was excited by an excitation signal from the excitation module, and the response signal was collected using a signal acquisition module. Both the excitation signal and response signal or only the response signal was analyzed in a signal processing module and used for further quality evaluation. Excitation module and signal acquisition module are the key parts of hardware. Fast Fourier transform was the most commonly used algorithm in the signal processing.

4.2 Excitation techniques of the acoustic vibration method

Various techniques using acoustic vibration were developed for agro-products quality inspection. The impact method and forced method are two excitation methods in the excitation module (Taniwaki and Sakurai, 2010). The commonly used excitation devices of the two excitation methods are listed in Table 1. The main advantage of the impact method is short excitation duration, because an instantaneous fore is applied to the sample in the impact method. One of the commonly used impact devices was the hammer or stick (Figure 6a). A problem of such device was that the repeated measurement was difficult to be provided. A pendulum (Figure 6b) can provide almost repeatable excitation by releasing it at the same angle. These excitation devices are simple and low-cost, so they are suitable for a fast on-line detection.

The other commonly used excitation method is the forced vibration (Figure 6c and 6d). In the forced vibration method, a varying fore was usually applied to the sample during measurement. The most commonly used instrument in forced vibration was the electrodynamic vibrator (Terasaki et al., 2001; Blahovec et al., 2007; Taniwaki et al., 2010; Abbaszadeh et al., 2013b; Zhang et al., 2014b). The advantage of forced vibration method is its good repeatability compared with the impact method. However, the forced vibration method was time-consuming, and cannot meet the demand of fast detection of an on-line detection system. In addition, there are random and swept sine wave excitations in the forced vibration excitation. The random excitation method generally used a force in a wide frequency range, and such method was used in some studies (Abbaszadeh et al., 2011; Abbaszadeh et al., 2013b; Abbaszadeh et al., 2014). The swept sine wave excitation was used more frequently than the random wave excitation. In the swept sine wave excitation method, the frequency was continuously varying (rising or declining) over a frequency range. Resonance frequency can be measured precisely in the swept sine wave excitation method because the excitation energy is concentrated in a certain frequency

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at some point (Taniwaki et al., 2010; Taniwaki and Sakurai, 2010). Therefore, the swept sine wave excitation was widely used in the existing studies (Finney, 1970; Abbott et al., 1992; Muramatsu et al., 1997; Muramatsu et al., 1999; Taniwaki et al., 2009a; Taniwaki et al., 2010; Cui et al., 2015; Zhang et al., 2015a).

4.3 Vibration measurement sensors of the acoustic vibration method

Acoustic vibration techniques can also be classified based on the vibration measurement sensors. There are contact and non-contact sensors for vibration measurement in the signal acquisition module (Table 2). Contact sensors directly contact with the surface of agro-products. Such sensors mainly include the acceleration pickup (Figure 7a) and piezoelectric sensor (Figure 7b). However, the attachment of contact sensor would add extra weight to the tested sample to affect its original vibration, and even damage the surface of agro-products. Therefore, contact sensors were generally used in laboratory studies, and more and more non-contact measurements were proposed in the acoustic vibration method.

The microphone (Figure 7c) was a widely used non-contact sensor in researches and applications (Chen et al., 1992; Zude et al., 2006; Valente et al., 2009; Mendoza et al., 2012). A problem of microphone was that the obtained response signal was easily affected by environmental noise. Another commonly used non-contact sensor is laser Doppler vibrometer (LDV, Figure 7d). The laser Doppler vibrometer, as an optical detection method, detected the

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vibration by measuring the frequency shift between the incident and reflected laser. Muramatsu et al. (1997) compared the detection results obtained by the accelerometer and laser Doppler vibrometer, and demonstrated that the vibration parameters obtained using a laser Doppler vibrometer were more accurate. However, LDV was high cost and needed a strong and stable reflected laser beam. In some studies, the load cell or accelerometer was attached to a plate, and the tested sample was dropped onto the plate (García -Ramos et al., 2003; Mireei et al., 2015). Such indirect measurement can also be considered to be a kind of non-contact measurement.

The microphone, as a non-contact sensor, has been used in commercial instrument. For example, the acoustic firmness detection instrument commercialized by AWETA (Nootdorp, the Netherlands). For on-line detection (De Belie et al., 2000; Hosainpour et al., 2011), microphones must overcome the effect of ambient noise. Laser Doppler vibrometer was not affected by the noise. However, the swept sine wave excitation was used in most studies using laser Doppler vibrometer, which cannot meet the demand of fast detection. Therefore, increasing demands for accurate, fast and cost-effective measurement remain a challenge for the acoustic vibration method.

Table 3 shows some typical applications of acoustic vibration methods in quality evaluation of different agro-products. The above mentioned excitation methods and vibration measurement sensors were used, and the equipment manufacturers are listed in the table. In addition, acoustic vibration parameters used in these studies are also shown in the table.

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5.Comparison of acoustic vibration methods and traditional destructive methods

Most existing studies on quality inspection of agro-products based on acoustic vibration were focusing on texture measurement. Therefore, the primary concern was the correlation between the vibration parameters measured by acoustic vibration methods and texture indices measured by traditional destructive methods. Good correlations were found in many studies, demonstrating that the acoustic vibration method is a feasible and reliable way for texture evaluation of agro-products.

However, it is also worth noting that there are differences in detection principle of the two detection approaches. On a micro level, acoustic vibration characteristics of agro-products are mainly determined by the cell turgor pressure (Hertog et al., 2004; Lu et al., 2005). The cell turgor pressure declined along with the process of cell water loss, so acoustic vibration characteristics of agro-products continuously varied during storage. For example, the resonance frequencies of fruits continuously decreased in the storage period (Taniwaki et al., 2009a; Zhang et al., 2015a). Magness-Taylor firmness, measured by the puncture test, varied along with the degradation of cell wall structure (Sirisomboon et al., 2000; Hertog et al., 2004). In addition, the cell wall-degrading enzyme is the key role in the degradation process. Therefore, the variation trend of acoustic firmness may be not consistent with that Magness-Taylor firmness (Baritelle et al., 2001; Zhang et al., 2015a). Similarly, correlations between Magness-Taylor firmness and acoustic firmness may be not good in some fruit varieties (Shmulevich et al., 2003;

Molina-Delgado et al., 2009; Zhang et al., 2014a; Zhang et al., 2015a; Yurtlu, 1999). This was because the results measured by the two methods reflected different aspects of texture of agro-products.

Aside from the correlation, the repeatability and sensitivity also need to be considered to assess a new method. Vibration parameters, especially the resonance frequencies, showed quite good repeatability in many studies (Yamamoto et al., 1980; Armstrong et al., 1990; Chen et al., 1992; Wang et al., 2004; Wang et al., 2006; Tiplica et al., 2010). The resonance frequencies, which describe the overall elasticity characteristics of pears, are not significantly affected by detection conditions. The resonance frequencies of a tested sample were not affected by testing conditions. However, the detection results by traditional destructive methods were different at testing sites because of anisotropism of fruit tissue (Abbott and Lu, 1996). The research results of Zhang et al. (2015c) showed that the acoustic vibration method using an LDV had better repeatability than the destructive puncture test.

The relative value loss was generally used to evaluate the sensitivity of an index (Shmulevich et al., 2003; Pan and Tu, 2004; De Ketelaere et al., 2006; Zhang et al., 2015c). Shmulevich et al. (2003) showed that the sensitivity of acoustic firmness was higher than that of penetration firmness of apples. Murayama et al. (2006) observed that *EI* of pears continuously declined during storage, but the penetration firmness remain stable in the initial stage. Zhang et al. (2014a; 2015c) also concluded that the sensitivity of *EI* of pears was higher than that of the penetration

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firmness. De Belie et al. (2000) designed an automated firmness monitoring system for apples, and found that the sensitivity of acoustic vibration technique was greater than that of penetrometer measurement.

In general, the acoustic vibration methods are not only able to evaluate texture of agro-products but also are superior to traditional destructive detection methods in terms of repeatability and sensitivity.

6.Conclusion

The acoustic vibration method is one of the most widely used methods for quality inspection of agro-products. For commercial application of the acoustic vibration method, one approach is to develop portable instruments, and the other one is to develop automatic detection lines. Fast detection speed is required in both applications. The excitation and signal acquisition modules are the key parts in the method. Contact measurement may prevent the free vibration and damage the surface of agro-products. Therefore, contact measurement was generally used in laboratory studies. In addition, contact measurement was also not suitable for on-line detection. More and more researches are focusing on non-contact measurement. Increasing accuracy and detection speed and reducing cost in the non-contact measurement is critical in the further research.

To assess a new acoustic vibration method, the correlations between acoustic vibration parameters and quality indices were mainly considered in most studies. However, the

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instrumental quality indices may be not related to human sensation, thus the correlation may be meaningless. The repeatability and sensitivity are also very important for a new method. Stable and accurate response signal is the foundation for further analysis. The acoustic vibration method showed the potential in repeatability and sensitivity compared with the traditional destructive method. Besides correlation, more consideration in repeatability and sensitivity should be paid to assess a new method.

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Table 1. Excitation methods and commonly used excitation devices in the acoustic vibration method.

Excitation methods	Advantages	Disadvantages	Excitation devices	References
Impact method	• Short excitation duration • Device is simple • Wide frequency range	• Some methods are unrepeatable • Possible to damage samples	Hammer, stick	Armstrong et al., 1990; Chen et al., 1992; Armstrong et al., 1997; Duprat et al., 1997; De Belie et al., 2000.
			Pendulum	Gomez et al., 2005; Wang et al., 2006; Wang et al., 2006; Lu et al., 2009.
Swept sine wave method	• Repeatable measurement • Energy can be concentrated in a narrow frequency band	• Device is costly • Long excitation duration	Vibrator	Finney, 1970; Abbott et al., 1992; Muramatsu et al., 1997; Muramatsu et al., 1999; Terasaki et al., 2001; Blahovec et al., 2007; Taniwaki et al., 2009a; Taniwaki et al., 2010; Abbaszadeh et al., 2011; Abbaszadeh et al., 2013a; Abbaszadeh et al., 2014; Zhang et al., 2014b; Cui et al., 2015; Zhang et al., 2015a.
			Speaker	Muramatsu et al., 1997; Fumuro et al., 2013.
			Piezoelectric vibration generator	Takahashi et al., 2010.

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Table 2. Vibration measurement methods and commonly used detection sensors in the acoustic vibration method

Vibration measurement methods	Sensors	Advantages	Disadvantages	References
Contact	Accelerometer	• Stable and commonly used	• Prevent free vibration of samples • Possible to damage the surface of samples	Finney, 1970; Abbott et al., 1992; De Belie et al., 2000; Chen et al., 2011.
	Piezoelectric sensor			Wang et al., 2006; Kadowaki et al., 2012; Macrelli et al., 2013a; Macrelli et al., 2013b.
Non-contact	Microphone	• Low cost • Non-contact	• Affected by environmental noise	Chen et al., 1992; Chen & De Baerdemaeker, 1995; Zude et al., 2006; Molina-Delgado et al., 2009; Valente et al., 2009; Mendoza et al., 2012.
	Laser Doppler vibrometer	• Not affected by environment al noise • Non-contact	• Device is costly • Need a reflective surface	Muramatsu et al., 1997; Murayama et al., 2006; Taniwaki et al., 2009a; Taniwaki et al., 2009b; Abbaszadeh et al., 2013b; Abbaszadeh et al., 2014; Oveisi et al., 2014; Zhang et al., 2014b.

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Table 3. Typical applications of acoustic vibration methods in quality evaluation of agro-products

Object	Excitation methods	Excitation devices	Vibration measurement sensors	Acoustic vibration parameters	Quality indices	References
Apple	Impact	A plastic piston	Acoustic firmness sensor (Model DTF v0.0.0.105, AWETA, Nootdrop, Netherlands)	$f^2m^{2/3}$	Firmness	Mendoza et al., 2012
	Impact	A plastic piston with a spherically shaped end	Acoustic firmness sensor (Model DTF v0.0.0.82, AWETA G&P, Nootdrop, the Netherlands)	Stiffness factor ($f^2m^{2/3}$)	Firmness	Molina-Delgado et al., 2009
	Impact	A solid plastic rod	Microphone (Model ECM-2005, Monacor)	Stiffness factor ($f^2m^{2/3}$)	Firmness	De Belie et al., 2000
	Impact	A hand-held rod	Microphone (Model 4176, B&K, Co., Denmark)	f, $f^2m^{2/3}\rho^{1/3}$	Firmness, lightness, hue, chroma	Duprat et al., 1997
	Swept sine wave (5-2000 Hz)	Electromagnetic vibrator (Model EA 1500, MB dynamics, Cleveland, USA)	Accelerometer (Model 2222, Endevco, California, USA)	f_1, A_1, f_2, A_2, f_2^2m, f and A at valley	Firmness, SSC, TA, ripeness	Abbott et al., 1992

	Impact	A hammer with a ball of was	Microphone (Radio Shack electret 270-090)	f, predicted modulus of elasticity	Firmness, modulus of elasticity	Armstrong et al., 1990
	Swept sine wave (5-10000 Hz)	Electromagnetic vibrator (Model EA 1250, MB Electronics, USA)	Accelerometer (Model 2222, Meggitt's Endevco Co., USA)	f_1, f_2, stiffness coefficient (f_2^2m)	Young's modulus, shear modulus, Magness-Taylor force, etc.	Finney, 1970
Pear	Swept sine wave (200-2000 Hz)/Impulse	Vibrator (Model ES-05, Dongling Vibration Test Instrument Co., Ltd., Suzhou, China)	LDV (Model LV-S01; Sunny Instruments Singapore Pte., Ltd., Singapore)	f_2, f_3, A_2, A_3, $f_2^2m^{2/3}$, $f_3^2m^{2/3}$, phase shift, vibration features in time and frequency domains, etc.	Stiffness, firmness, variety discrimination	Zhang et al., 2014a; Zhang et al., 2014b; Zhang et al., 2015a; Zhang et al., 2015b
	Swept sine wave (100-1000 Hz)	Vibrator	Piezoelectric sensor (Model NSP-1; Applied vibro-Acoustics Inc., Hiroshima, Japan)	f_2, f_3, $f_2^2m^{2/3}$, $f_3^2m^{2/3}$, $f_2^2d^2$	Detection of core rot symptom	Kadowaki et al., 2012
	Swept sine wave (0-2 kHz)	Electrodynamic shaker (Model 513-B, EMIC Co., Tokyo,	LDV (Model LV-1720, ONO SOKKI Co. Ltd, Yokohama, Japan)	EI	Sensory evaluation, texture index	Taniwaki et al., 2009b

		Japan)				
	Swept sine wave (0-3 kHz)	Vibration generator (Modal 512A; EMIC Co. Ltd., Tokyo, Japan)	LDV (Model LV-1300; ONO SOKKI Co. Ltd, Yokohama, Japan)	*EI*	Firmness, sensory evaluation	Murayama et al., 2006; Terasaki et al., 2006
	Impact	A pendulum with a plastic ball	Piezoelectric film sensor	Stiffness coefficient ($f^2m^{2/3}$), elasticity coefficient ($f^2m^{2/3}\rho^{1/3}$)	Firmness	Gomez et al., 2005
Kiwifruit	Swept sine wave (20-3000 Hz)	Electrodynamic shaker (Model LB-512A, EMIC Co. Ltd., Tokyo, Japan)	LDV (Model LV-1300, ONO SOKKI Co. Ltd, Yokohama, Japan)	*EI*	\	Terasaki et al., 2013
	Swept sine wave (20-3000 Hz)	Vibration generator (Model G21-001, Shinken, Co. Ltd., Tokyo, Japan)	LDV (Model LV-1300; ONO SOKKI Co. Ltd, Yokohama, Japan)	Stiffness coefficient ($f_2^2m^{2/3}$), loss coefficient	SSC, firmness, ripeness (sensory evaluation)	Terasaki et al., 2001
Watermelon	Random wave (0-1	Electrodynamic shaker (Model LSD	LDV (Model Ometron VH1000-D, B&K,	Vibration features	Firmness, sensory	Abbaszadeh et al., 2011; Abbaszadeh et

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	kHz)	V721, Low Force Shaker, B&K, Co., Denmark)	Co., Denmark)		evaluation	al., 2013a; Abbaszadeh et al., 2013b; Abbaszadeh et al., 2015
	Impact	A metal ball fixed on a pendulum	Microphone (Model 4189, B&K, Co., Denmark)	*f*, maximum amplitude, band magnitude	Hollow detection, ripeness	Diezma-Iglesias et al., 2004
Melon	Swept sine wave (100-1000 Hz)	Electrodynamic shaker (Model 513-B, EMIC Co., Tokyo, Japan)	LDV (Model LV-1720, ONO SOKKI Co. Ltd, Yokohama, Japan)	*EI*	Sensory evaluation	Taniwaki et al., 2010
	Swept sine wave (0-1000 Hz)	Electrodynamic shaker (Model 513-B, EMIC Co., Tokyo, Japan)	LDV (Model LV-1720, ONO SOKKI Co. Ltd, Yokohama, Japan)	*EI*	Sensory evaluation	Taniwaki et al., 2009c
Tomato	Air pressure/Impact	Air bellow/An electromagnet probe	A low-mass impact sensor (Sinclair iQ^{TM}-Firmness Tester, Sinclair International Ltd, Norwich, England)/Acoustic firmness sensor (AFS, AWETA, Nootdrop,	SIQ-FT index/Firmness index ($f^2m^{2/3}$)	\	De Ketelaere et al., 2006

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			the Netherlands)			
	Impact	A solid plastic rod	Microphone (Model MC101)	Stiffness factor ($f^2m^{2/3}$)	Firmness	Schotte et al., 1999
Peach	Impact	A pendulum with a wooden (or aluminum alloy, or plastic) ball	Piezoelectric sensor	Stiffness coefficient ($f^2m^{2/3}$)	Firmness	Wang et al., 2006
Pitaya	Swept sine wave (0-3 kHz)	Speaker	A portable vibration measurement equipment (Model Vp-2, Seibutsu-Sindo-Kenkyusyo, Hiroshima, Japan)	*EI*	Peel color, firmness, TSS, etc.	Fumuro et al., 2013
Dates	Drop	A conveyor unit	Load cell (Model PW6CMR, HBM Inc., Marlborough, MA, USA)	Vibration features, the first half-wave	Firmness	Mireei et al., 2015
Avocado	Impact	Self-fabricated hammer	Two LDVs (Model CLV 1700 and 2534, Polytec UK Ltd., UK)	*f*	Firmness	Landahl & Terry, 2012
Grape	Swept sine wave (0-5 kHz)	Piezoelectric vibration generator	Piezoelectric vibration detector	*EI*	Firmness	Takahashi et al., 2010
persimmon	Swept sine wave (0-2	Electrodynamic shaker	LDV (Model LV-1720, ONO	*EI*	Sensory evaluation,	Taniwaki et al., 2009a

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	kHz)	(Model 513-B, EMIC Co., Tokyo, Japan)	SOKKI Co. Ltd, Yokohama, Japan)		texture index	
guava	Swept sine wave (5-1000 Hz)	Shaker	Accelerometer (Model 8778A500, Kistler Accelerometer)	*f*, *EI*	Maturity index, firmness, stiffness	Mayorga-Martínez et al., 2016
Preserved egg	Impact	A plastic stick with silicon	Accelerometer (Model 35C23, PCB Piezo-tronics, Inc., New York, USA)	Decay rate	Egg gel inspection	Chen et al., 2011
Potato	Drop	A belt conveyor	Microphone (Model VM-034CY, Panasonic Electret)	Magnitude, power spectral density, *f*, etc.	Potato and cold detection	Hosainpour et al., 2011

Abbreviations: SSC: soluble solids concentration; TA: titratable acidity; TSS: total soluble solid; LDV: laser Doppler vibrometer; d: diameter; ρ: density; f: resonance frequency; f_1: the first resonance frequency; f_2: the second resonance frequency; f_3: the third resonance frequency; A: amplitude; A_1: amplitude at f_1; A_2 amplitude at f_2; EI: elasticity index ($f_2^2 m^{2/3}$).

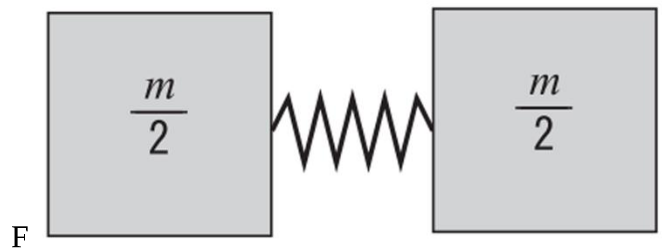

Figure 1. Mass–spring model for an elastic body of mass *m* (Taniwaki and Sakurai, 2010).

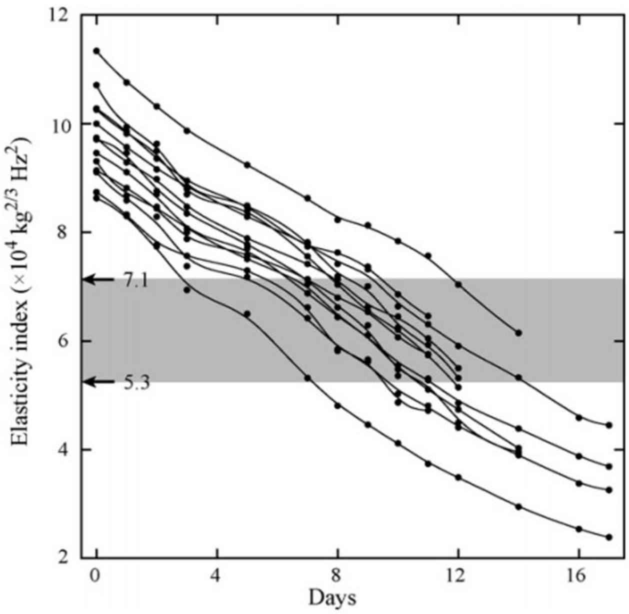

Figure 2. Changes in the elasticity index (*EI*) of individual melon samples. The shaded areas indicate the optimum ripeness in terms of the *EI* (5.3–7.1 × 10^4 kg$^{2/3}$ Hz^2) (Taniwaki et al., 2010).

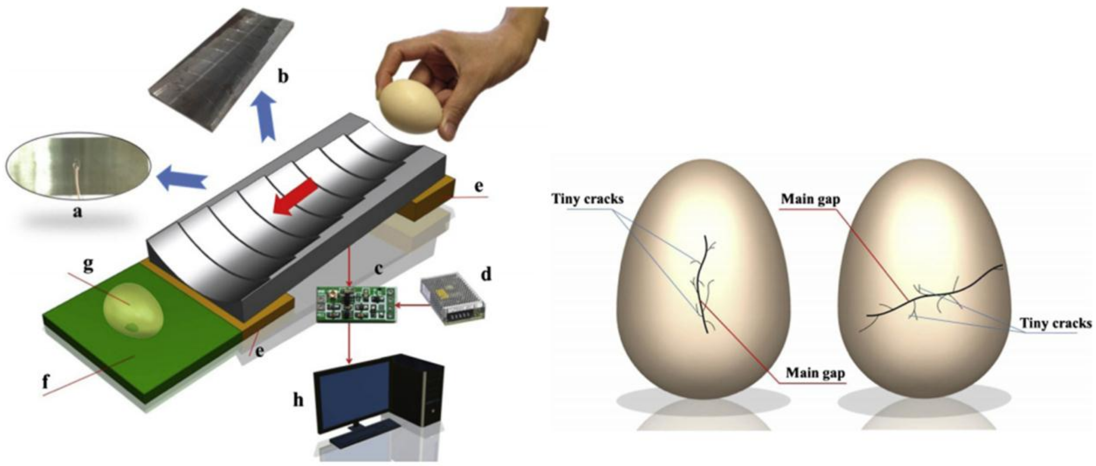

Figure 3. Diagram of eggshell crack detection device (Jin et al., 2015).

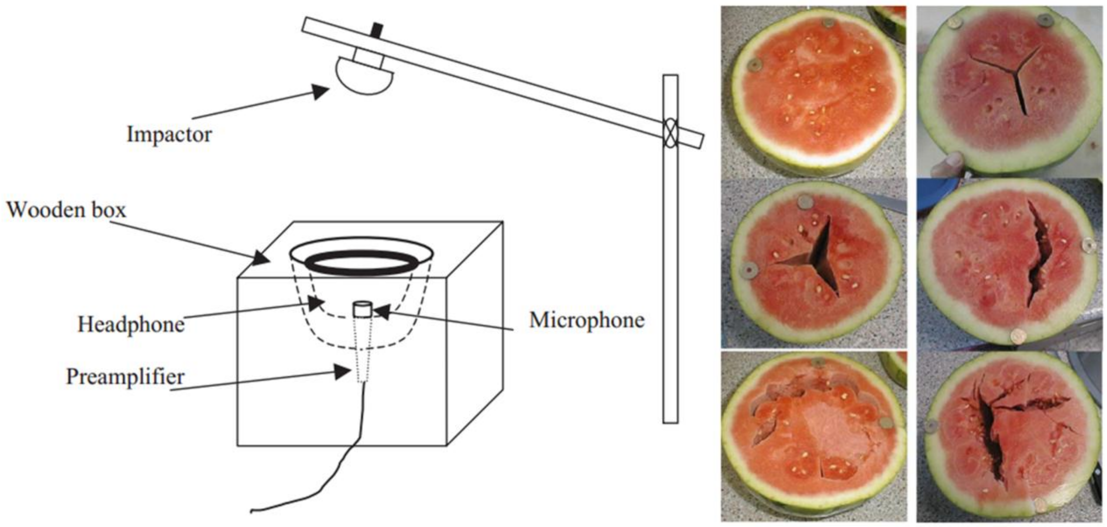

Figure 4. The diagram of the acoustic vibration device for watermelon hollow detection (Diezma-Iglesias et al., 2004; 2005).

Figure 5. The general process of acoustic vibration method for quality evaluation of agro-products.

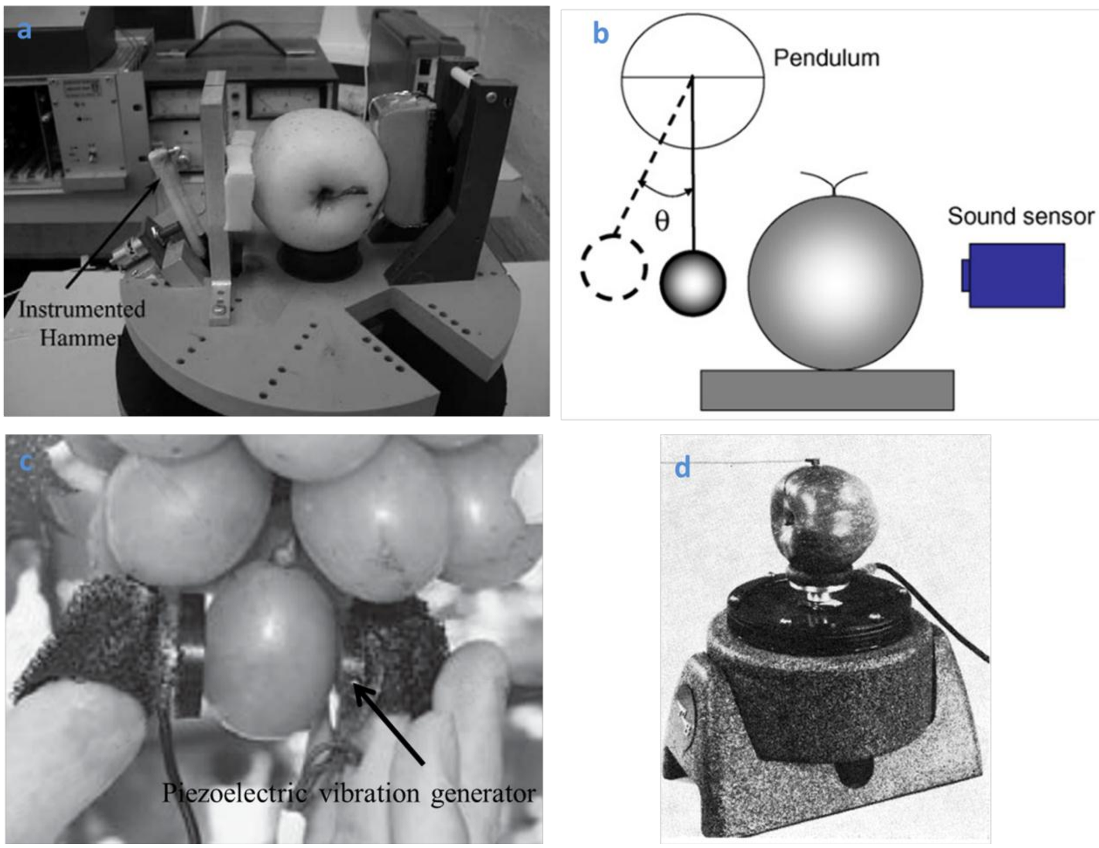

Figure 6. Commonly used excitation devices: (a) hammer (Shmulevich et al., 2003); (b) pendulum (Baltazar et al., 2007); (c) piezoelectric vibration generator (Takahashi et al., 2010); and (d) vibrator (Finney, 1970).

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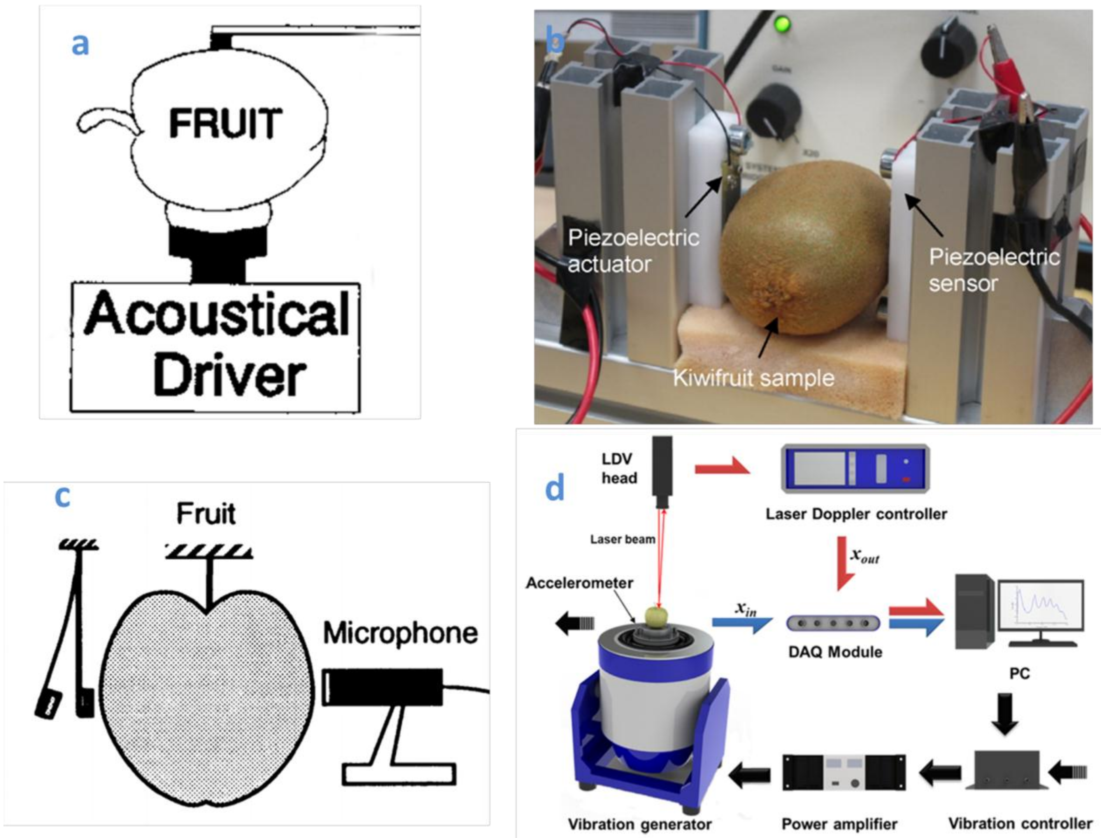

Figure 7. Commonly used vibration measurement sensors: (a) accelerometer (Abbott et al., 1992); (b) piezoelectric sensor (Macrelli et al., 2013b); (c) microphone (Chen et al., 1992); and (d) laser Doppler vibrometer (Zhang et al., 2016).

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