Spanish Journal of Agricultural Research (2005) 3(1), 52-60

Vibrational analysis of seedless watermelons: use in the detection of internal hollows

B. Diezma Iglesias*, M. Ruiz-Altisent and P. Jancsók

Department of Rural Engineering. Physical Properties Laboratory. Polytechnic University of Madrid. ETSIA. Avda. Complutense, s/n. 28040 Madrid. Spain

Abstract

The internal quality of fruit can be non-invasively tested using systems based on vibrational characteristics. In this work, acoustic impulses were used to detect internal hollows in watermelons; the change in the signal revealing the problem. Frequency spectrum variables were analysed for their potential as non-destructive predictors of this defect. The band magnitude variables, obtained from the integral of the spectrum magnitudes between two frequencies, best predicted internal disorders. Experimental modal analysis was used to investigate the vibrational performance of watermelons and to determine the best positions for the impact point and response measurement microphone. A first-type spherical mode and its resonant frequency was the best indicator of internal quality problems. Finite element modal analysis was performed to establish a watermelon shape/characteristics model and to compare theoretical and experimental results.

Additional key words: acoustic impulse response, experimental modal analysis, non-destructive methods.

Resumen

Análisis de las vibraciones de las sandías apirenas aplicado a la detección de ahuecados internos

Algunos métodos no destructivos para la determinación de la calidad interna de frutas están basados en las características vibratorias de éstas. En esta investigación se ha analizado en la pulpa de las sandías la respuesta acústica al impacto para la detección de cavidades, que deterioran la calidad del fruto. Se examinaron diferentes parámetros extraídos del espectro en frecuencias como potenciales predictores no destructivos de este desorden interno. Los parámetros espectrales con mayor capacidad discriminante para estos defectos son las llamadas magnitudes de banda, obtenidas integrando la amplitud de la señal en el espectro entre dos frecuencias en un específico ancho de banda. El análisis modal es el proceso por el cual se determinan los parámetros modales, pudiendo tratarse de una técnica teórica (análisis modal con elementos finitos) o experimental (análisis modal experimental). Se ha aplicado un análisis modal experimental a las sandías para explicar su comportamiento vibratorio, así como para verificar que las localizaciones del punto de impacto y del micrófono para recoger la señal en el ensayo acústico son las más adecuadas. El mejor indicador de los problemas de calidad interna ha sido uno de los modos de vibración esféricos, y su correspondiente frecuencia resonante. Se ha realizado un análisis modal con elementos finitos para establecer un modelo en sandía y comparar los resultados obtenidos mediante esta técnica teórica y la experimental.

Palabras clave adicionales: análisis modal experimental, métodos no destructivos, respuesta acústica al impacto.

Introduction

The development of non-destructive techniques, including the use of acoustic and vibrational characteristics, for assessing the internal properties of fruits and vegetables (mainly related to flesh texture) has been the subject of a number of research projects. Several techniques (Chen and Sun, 1991; Abbott, 1999) and theoretical models (Cooke and Rand, 1973; Huarng *et al.,* 1993) concerning the vibrational performance of these biological materials have been developed.

When an object is excited in the audible or non-audible range of frequencies it responds by vibrating. The amplitude peaks obtained in the frequency spectrum

* Corresponding author: bdiezma@upm.es
Received: 08-03-04; Accepted: 16-12-04.

B. Diezma Iglesias and M. Ruiz-Altisent are members of the SEA.

are its resonant frequencies, the appearance of which is related to the elasticity, density, size and shape of the object. The resonant frequencies of some fruits and vegetables (apples, melons, peaches, tomatoes etc.) have been associated with firmness, and «stiffness» or «firmness» coefficients have been recorded for them. The stiffness coefficient was formerly defined as f^2m (Abbott *et al.,* 1968), where f is a selected resonant frequency and m the mass of the fruit. This was later corrected and replaced by the expression $f^2m^{2/3}$ (Cooke, 1972), thought to be a mass-independent indicator of firmness. Depending on the citing author and the use of the equation, f can be the first, second or third resonant frequency. In the determination of peach firmness, the second resonant frequency is used (Clark and Shackelford, 1973); for testing the texture of apples, the second or third resonant frequencies can be used (Abbot and Liljedahl, 1994), while for pineapples the first resonant frequency is used (Chen and De Baerdemaeker, 1993a). The correlations between the textural characteristics of fruits and vegetables and other vibrational or sonic variables, e.g., pulse propagation velocity, damping coefficient and band magnitude, have also been studied (Garret and Furry, 1972; Sugiyama *et al.*, 1998).

Consumers often attempt to determine the maturity and/or post-harvest ripeness of melons and watermelons by listening to the sound produced after manually striking them. A number of researchers have tried to verify this method by studying the responses of fruits subjected to acoustic impulses produced by an impacting body (Stone *et al.*, 1996; Armstrong *et al.,* 1997; De Belie *et al.*, 2000; Jancsók e*t al.*, 2001). Indeed, an acoustic impulse response technique has now been developed as a non-destructive method for detecting internal creases or voids in seedless watermelons (Diezma *et al.,* 2002).

The introduction of tastier, seedless cultivars has increased the consumption of watermelons. However, these triploid varieties can suffer an internal problem known as «hollow heart». This is most likely to occur early in the season or when growing conditions alternate between wet and dry and when there are wide swings in temperatures. Poor pollination rates and excessive irrigation and nitrogen fertilization can also lead to hollow heart problems and off-flavours. The percentage of affected fruits varies significantly and can range from nil up to $>50\%$, depending on the batch. While small hollows may not dramatically affect table quality or shelf life, larger volumes tend to reduce freshness and flavour.

Any free or forced response of a structure to vibration can be modelled as a discrete set of vibrational modes. The modal parameters of each mode within the frequency range of interest provide a complete vibrational description of the structure. Modal analysis is the process of determining the modal variables, and this may be accomplished using theoretical or experimental techniques. A comprehensive understanding of structural vibration is essential in the design and development of new structures (buildings, machines, etc.) as well as for solving noise and vibration problems in existing structures (Dossing, 1988). Modal analysis is an efficient technique for describing, understanding and modelling structural performance, and is widely used in different industries (e.g., car manufacturing). The same techniques can also be applied to fruits and vegetables.

The mathematical modelling of the characteristics of a linearly elastic, isotropic and homogeneous spherical solid allows its mode shapes to be classified as torsional, longitudinal or spherical (Cooke and Rand, 1973). Using theoretical models, some resonant frequencies have been associated with certain vibrational modes in fruits. For example, in apples, more than a dozen basic vibrational modes have been explained and the main resonant frequency obtained by exciting fruits at the equator. This resonant frequency represents a pure compression mode (Armstrong *et al.,* 1990).

Several authors have used modal analysis to study the vibration characteristics of fruits and vegetables (Chen *et al*., 1996; Jancsók *et al.*, 2001). The identification of the vibrational modes corresponding to each resonant frequency may be useful for determining which are related to fruit quality properties.

The main aims of this study were: i) to use modal analysis as a tool for the non-destructive assessment of watermelon quality by analysing and comparing the mode shapes and resonant frequencies of watermelons with different quality characteristics, and ii) to optimise the location of the excitation impulse and the response sensor (for measuring the resonant frequency of interest) of an acoustic device developed for detecting hollow heart in watermelons. Most sensors only detect modes of vibration with radial deformation (spherical modes) and do not register transverse deformation: the detection of spherical modes is important in practice and is the focus of this article.

Material and Methods

Impact acoustic response measurements: experimental determination of the resonant frequency

Acoustic measurements were made using a device (patent pending) designed and optimised (in terms of shape, size, structural components, excitation method and recording system) for use with watermelons. The acoustic response of these fruits was measured by striking a point on the equator with an impactor, and detecting the output sound using a microphone on the opposite side. The impactor was made of a metal ball (13 g) fixed to a bar which was dropped onto the fruit from a height of 120 mm.

The instrument used to acquire the acoustic impulse information was a prepolarized free-field ½” (11.5 mm) microphone (frequency range 6.3-20 kHz; sensitivity 50 mV Pa^{-1}). A signal conditioning amplifier supplied the power; this provides proper electrical loading to the transducer, amplifies the signal, and allows the use of several low- and high-pass filters. A microphone pre-amplifier completed the recording system. A data acquisition card (tuneable sampling rate of up to 40 kHz) connected the external system to a computer. Windows-based software was developed for the control of the process and data acquisition. This software plots acoustic signal intensity against time and saves the results in an ASCII file.

Fast Fourier transformation (FFT) of the signal was used to determine the frequency spectrum and its natural frequencies. Sampling at 40 kHz for 4096 Fourier coefficients resulted in a frequency resolution of 9.77 Hz. Each spectrum was normalized by dividing the magnitude at each frequency by the maximum magnitude of the measured spectrum. Different acoustic variables were obtained for spectral characterisation, including the resonant frequency of maximum amplitude and several band magnitude variables (BM). These were calculated from the integral of the spectrum magnitudes between two frequencies. To determine the optimal BM, several intervals were defined (Table 1).

Table 1. Frequency limits for BM analysis

BM	Frequency limits (Hz)
BM_1	85-160
BM_2	40-90
BM_3	60-110
BM_4	70-120
BM_5	80-130
BM_6	100-180
BM_7	120-200

The structural support of the equipment is provided by a wooden box with a shallow hollow on its upper side, lined with a covering of padding material (Fig. 1). The microphone and preamplifier are placed in the hollow. The receptacle insulates the microphone area while the padding material provides the necessary free support. The microphone detects the acoustic impulse response 2-5 mm from the surface of the fruit; it never touches it.

Previous research (Diezma *et al.,* 2002) has shown that this acoustic response device can be used to non-destructively classify watermelons into quality classes according to their status with respect to internal flesh creases and hollows. The BM variables were the best indicators of internal quality, especially the range between 85 and 160 Hz.

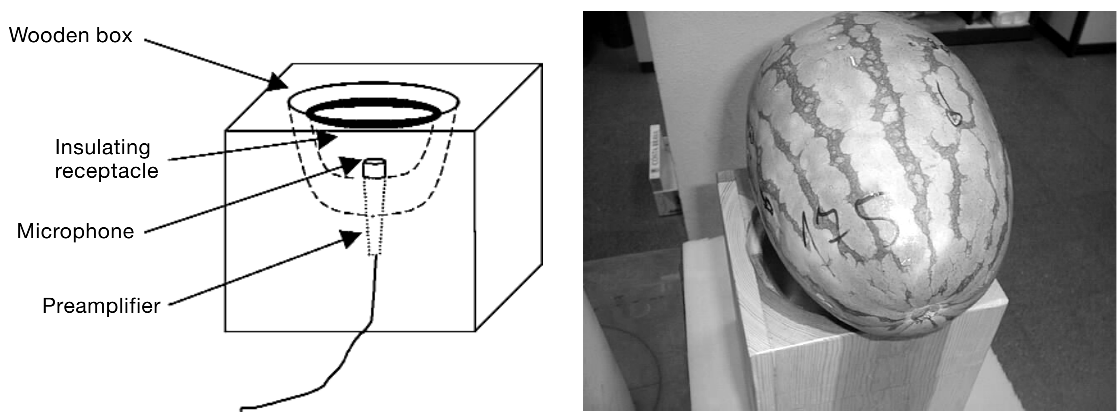

Figure 1. Structural elements of the impact acoustic response device. Left: diagram showing the structural elements and microphone. Right: watermelon awaiting excitation at an equatorial point.

In this study, the acoustic responses of 20 seedless watermelon cv. *Reina de Corazones* fruits (10 good watermelons and 10 with hollows; void volume 12-150 ml) were characterised. All weighed between 4 and 5 kg (Fig. 2). For each watermelon, three measurements were taken after striking the fruit at two positions: at a point on the equator, and then at 90º from the first point (still on the equator). The average for the six measurements was then calculated.

Experimental modal analysis of watermelons

Modal analysis is a process whereby a structure is described in terms of its natural characteristics of frequency, damping and mode shapes (or deformation patterns). If all of a structure's natural frequencies are excited, the corresponding deformation pattern is shown. All structures have natural frequencies and mode shapes. Basically, the weight and stiffness of the body determine where these exist.

Modal analysis outputs are the modal variables for each vibration mode: modal frequency, modal damping, and mode shape. Experimental modal analysis (EMA) is based on the frequency response function for the output response of a structure and the force applied to excite it. Both the applied force and the response are measured simultaneously. Once the data are sampled, the FFT algorithm is used to form linear spectra of the input excitation and output response. Due to this transformation, the function becomes a set of complex numbers; thus it contains real and imaginary descriptive components - or magnitude (also referred to as amplitude in this text) and phase components. The input power spectrum, the output power spectrum and the cross spectrum between the output and input signals are used to compute the frequency response function (FRF) and the coherence function. The FRF contains information regarding system frequency and damping. In an experimental modal analysis there are *n* places where forces can be applied and responses measured. This means a total of n^2 possible frequency response functions that could be acquired. A matrix of frequency response functions is thus obtained, which contains information regarding the mode shape of the system at the measuring locations. This matrix is symmetrical since the mass, damping and stiffness matrices that describe the system are also symmetrical. It is therefore unnecessary to measure all the terms of the frequency response function matrix. The coherence function is used as a data quality assessment tool which identifies the relationship between the input and output signals (Avitabile, 2001).

For EMA, two watermelons of similar volume and shape were studied: one with an internal hollow (120 ml void volume; fruit weight 4.33 kg), the other of optimal internal quality (fruit weight 4.88 kg). This selection was performed by experts (and later confirmed by cutting the fruit in half). Both watermelons were placed vertically on a padded support and struck by an impact hammer equipped with a force transducer (PCB Piezotronics GK291C80). The hammer weight was 0.16 kg, and the tip diameter that made contact with the fruit surface was 0.6 cm. Using modelling clay, a miniature accelerometer (PCB Piezotronics 353C22) was attached to the watermelon skin (with its axis normal to the local surface) in order to measure the response acceleration at that point and in the direction perpendicular to the surface. Five circumferences parallel to the equator (perpendicular to the calyx-stem axis) were drawn along the watermelon. On each circumference line, 12 points were marked following 12 meridians. Two further points were selected on the top and on the bottom of the fruit. These nodes were used as accelerometer location points (Fig. 3).

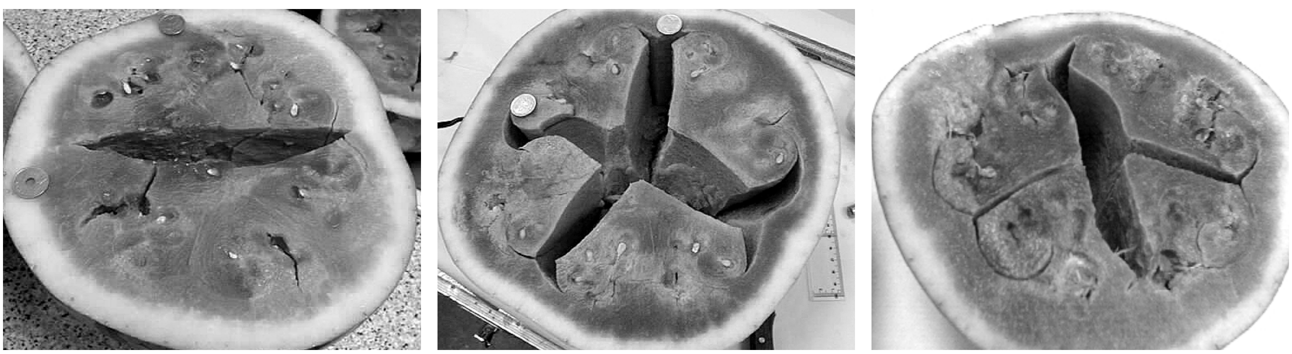

Figure 2. Hollows in watermelons with different positions and directions in the flesh.

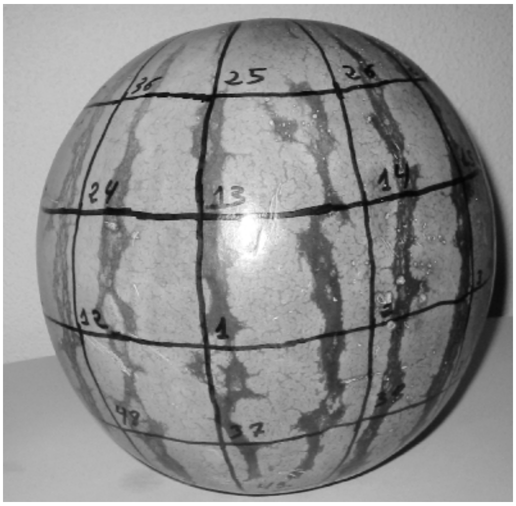

Figure 3. Network of points on surface of watermelons used in experimental modal analysis.

Three consecutive impacts were made at an equatorial node and the average input force and acceleration response recorded at other nodes in the network. During the test, the watermelon was placed on soft polyurethane foam which provided free support. The impact force and the accelerometer response were acquired by a DIFA-SCADASII 6-channel data acquisition board connected to an HP 9000/712 workstation running CADA-X v.3.4 software. The system calculated the frequency response and coherence functions, which provide a means of assessing the degree of linearity between the input and output signals.

The equipment and the procedures used in this modal analysis were developed in previous works by the researchers at the Laboratory for Agro-machinery and Processing of the Katholieke Universiteit Leuven (Belgium) (Jancsók *et al.*, 2001) where this experiment was performed.

The two watermelons used in the EMA were also subjected to an acoustic impulse response test. This was repeated 12 times on both watermelons at 12 different points. For each measurement the fruit was impacted at one equatorial point and the acoustic signal detected at the opposite equatorial point.

Finite element simulation of the vibrational properties of intact watermelons

Finite element (FE) modal analysis is a numerical method in which the natural frequencies and the mode shapes of objects are calculated. For FE analysis, an FE mesh must be generated. In this procedure the geometrical model is divided into elements interconnected by a number of nodes. Three degrees of freedom are allowed per node, since each can be displaced in three perpendicular directions.

To establish the FE model of the watermelons, the fruits were likened to an ellipsoid with a major axis of 24 cm and a minor axis of 19.2 cm (the dimensions of the optimal watermelon subjected to EMA). Flesh and skin were not distinguished but were considered isotropic. A Young's modulus of 4 MPa, a density of 800 kg m^{-3} and a Poisson ratio of 0.3 was considered for all finite elements; these values were obtained from the literature (Chen and De Baerdemaeker, 1993b) and from the authors' unpublished data. The non-linear visco-elastic texture of the fruit was simplified as a linear elastic texture. This simplification has been used in previous investigations (Chen *et al.,* 1996). The model was generated using the ANSYS program (ANSYS Inc., 2003). The defined finite elements (solid45) were composed of eight nodes. ANSYS is a general purpose finite element modelling package for numerically solving a wide variety of mechanical problems. The problem of the vibration modes was solved by this software using the subspace iteration method.

The first 30 modes of the watermelon were analysed. The mode shapes were identified by examining the deformation plot and the animated mode shape display.

Data analysis

One way ANOVA was used to select the best predictors of internal disorders in the impact acoustic response experiments. This analysis creates various descriptive statistics broken down by one or more categorical variables. To verify the ability of BM parameters to distinguish between watermelons with and without internal voids, several forward stepwise discriminant analyses were performed using all the BM_x variables extracted from the spectra. In each step 10% of the population (randomly selected) was removed. Forward stepwise analysis moves variables into the model in successive steps. At each step, the variable with the largest F value is chosen for inclusion. Stepping terminates when no other variable shows an F value greater than the «F to enter» value. In the present case, this was set to 1.0.

Figure 4. Mean and standard deviation of the band magnitude in the range 85-160 Hz (BM_1) for good and hollow watermelons (n = 20).

Results

Impact acoustic response measurements

For the group of 20 watermelons in the impact acoustic analysis test, one way ANOVA analysis showed that the BM between 85 and 160 Hz (BM_1), with the highest F-value (p-value = 10^{-6}), was the best predictor of internal voids. BM_1 values increased when internal voids appeared in the watermelons (Fig. 4). In addition, the resonant frequency of maximum amplitude of the good and the hollow watermelons was significantly different (194 Hz compared to 141 Hz; $\alpha = 0.05$) (Fig. 5; Table 2).

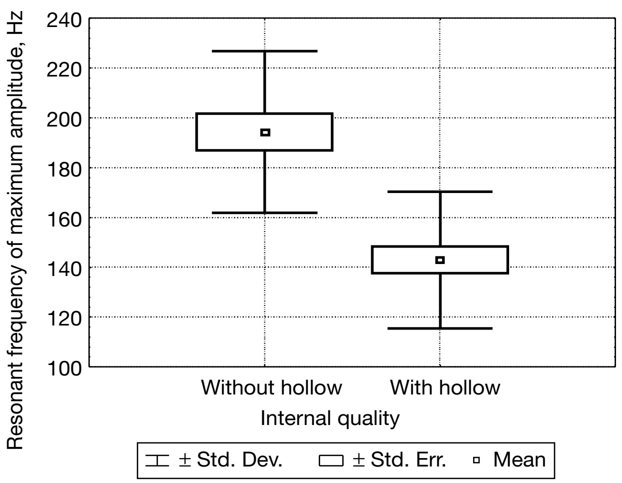

Figure 5. Mean and standard deviation of the resonant frequency of maximum amplitude for good and hollow watermelons (n = 20).

Table 2. Means and standard deviations of the resonant frequency of maximum amplitude obtained in the impact acoustic test for the group of 20 watermelons, and for the two watermelons analysed by experimental modal analysis.

	Resonant frequency of maximum amplitude (Hz)	
	Two watermelons (one in each group)	**20 watermelons (10 in each group)**
Without internal hollow	171 (12 repetitions per watermelon)	194 ± 32.5 (10 watermelons; six repetitions each)
With internal hollow	139 ± 13.55 (12 repetitions per watermelon)	141 ± 27.4 (10 watermelons; six repetitions each)

The acoustic variable BM_1 was included in the first step in all classification functions obtained from the discriminant stepwise analysis (Table 3).

In the impact acoustic test, the hollow watermelon also studied by EMA showed significant variability in its resonant frequencies of maximum amplitude (ranging from 125 to 156 Hz for the different impact points). In the good fruit, the same value was obtained at all the impact points (171 Hz).

Experimental modal analysis

In EMA, several kinds of mode shapes were obtained. The results with the better coherence functions were selected, and the mode shapes identified and displayed using the animation display module of the ANSYS programme.

The deformations of the good and damaged watermelons were compared. One of the observed modes was a first-type spherical mode also known as the longitudinal mode. This mode shows simultaneous extension and contraction in two perpendicular directions. During extension and contraction in the longitudinal direction (Y-axis), the watermelons contract and extend in the transverse direction (Fig. 6). This represents a Y-axisymmetric vibrational mode with one main axis along the Y-axis (the long axis of the watermelon) and another in the transverse plane orthogonal to the Y-axis in the centre of the fruit. The resonant frequency of this mode varied between the two watermelons: while in the hollow fruit the resonant frequency of the longitudinal mode was 129 Hz, in the good fruit this value was 172 Hz (Table 4).

Table 3. Regression coefficients and constant for the discriminant functions obtained by removing a random 10% from the sample at each step. Variables are shown in their selection order

	Function 1		Function 2		Function 3		Function 4	
	H^-	H^+	H^-	H^+	H^-	H^+	H^-	H^+
1. BM_1	–0.66	2.27	–0.66	2.22	–0.69	2.41	–0.57	2.88
2. BM_5	–1.32	–5.58	–1.20	–5.07	–1.19	–5.15	–0.92	–9.33
3. BM_2	0.99	–0.46	0.53	–0.38	0.54	–0.44	0.58	16.16
4. BM_4	2.64	7.22	1.03	–0.24	1.15	–0.10	2.59	–6.37
5. BM_6	0.52	–0.40	2.49	6.51	2.50	6.46	0.52	–0.62
Ct.	–10.35	–34.56	–10.47	–35.08	–11.01	–37.40	–9.48	–35.88

H^-: without hollow. H^+: with hollow.

Finite element simulation of the vibrational properties of intact watermelons

The first 30 modes obtained from the model were extracted and examined (the first six were discarded since they corresponded to rigid body modes). A first-type longitudinal mode was found at 186 Hz by the FE simulation. The deformation pattern of this mode was equivalent to that observed in the EMA: simultaneous extension and contraction in two perpendicular directions (Fig. 7).

Discussion

Location of excitation force and microphone position

Obtaining the resonant frequency of any mode shape by impact acoustic response experiments requires both the excitation and the microphone be adequately located and directed. The best location on the fruit surface must therefore be found where the mode of interest can be easily detected. When detecting internal defects in watermelons via the first-type longitudinal resonant frequency, the equator of the fruit was found to be a good location for the excitation point and the response sensor, in accordance with the deformation pattern of the first-type longitudinal vibration mode.

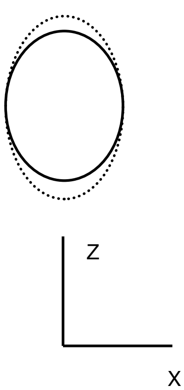

Figure 6. Vibration pattern of the first-type longitudinal mode shape obtained by experimental modal analysis.

Comparison of the resonant frequencies obtained by experiment and by finite element simulation

Some difference was seen in the resonant frequencies of the first-type longitudinal mode obtained by EMA and FE simulation. In the experimental test, the good watermelon had a value of 172 Hz, whereas the FE method obtained a value of 186 Hz (Table 4). This difference is perhaps due to the simplified assumptions of the simulation such as isotropic properties in the flesh and the skin, no distinction between regions in the watermelon, and the use of selected literature values for the Poisson ratio, Young's modulus and density. In pineapples (Chen and De Baerdemaeker, 1993a) it was concluded that FE models with homogeneous, linear and

Table 4. Resonant frequencies of the first-type longitudinal mode shape in experimental modal analysis and in the finite element simulation

	Resonant frequency of the first-type longitudinal mode shape (Hz)	
	Experimental modal analysis	Finite element simulation
No internal hollow	172	186
With internal hollow	129	Not simulated

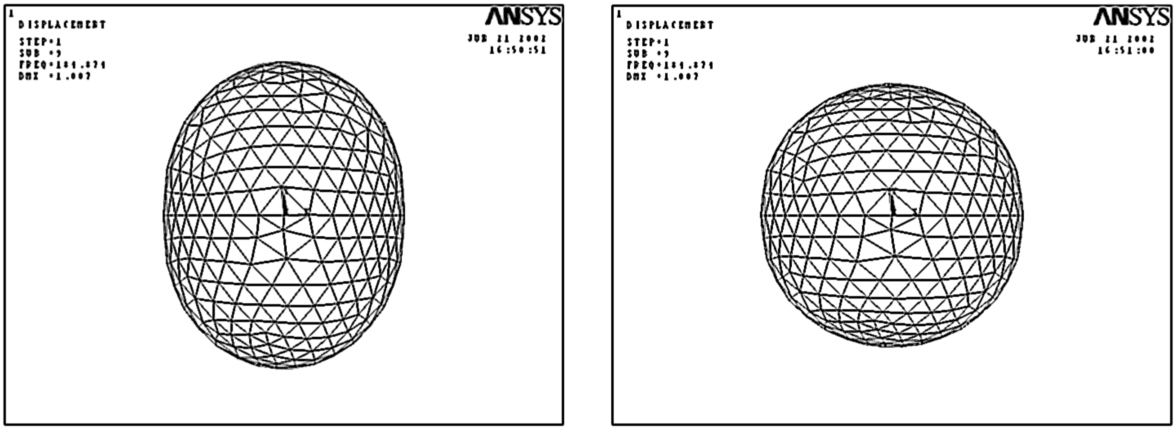

Figure 7. Display animation of the first-type longitudinal mode shape obtained by finite element simulation. Left: during extension in the longitudinal direction the watermelons contracted in the transverse direction. Right: during contraction in the longitudinal direction, the watermelons extended in the transverse direction.

elastic properties are acceptable for predicting the resonant frequency of first-type longitudinal mode shapes, assuming divergences of 30 Hz between FE and EMA results. Thus, the present results are acceptable. Simulation of the vibrational properties of watermelons could therefore be a useful tool for studying the influence of the position and direction of any hollows (with respect to the fruit axis or its texture characteristics) on the resonant frequency of the first-type longitudinal modal shape. Further simulations are necessary, however, to validate the present results.

Comparison of the resonant frequencies shown by hollow heart and good watermelons

The resonant frequencies of the longitudinal mode shape shown by EMA for the good and damaged watermelons differed: that of the good watermelon was 172 Hz, while the hollow fruit showed a value of 129 Hz. The first-type longitudinal resonant frequency measured by modal analysis agreed well with the impact acoustic response measurements. Thus, the good watermelon showed a resonant frequency of maximum amplitude at 171 Hz for all the impact points around its equator. However, in the hollow fruit, the mean value of the resonant frequency of maximum amplitude was 139 Hz. The data trend seems to indicate that it is the hollow heart inside the watermelon that causes the change in the resonant frequency of the first-type longitudinal mode shape.

Comparison of the impact acoustic test results for the two watermelons (also studied by modal analysis), and the batch of 20 watermelons, shows a consistent trend despite the great variability in resonant frequency observed (Table 2).

These results are consistent with those obtained for other non-homogeneous fruits such as pineapples or apples (Chen and De Baerdemaeker, 1993a), for which the use of the longitudinal mode is suggested for internal quality assessment.

BM_1 (obtained from the acoustic test) showed greater good/hollow discriminating power than did the frequency of maximum amplitude. The great variability in the frequencies of maximum amplitude (partly due to the resolution of the FFT calculation), plus the fact that BM_1 includes the resonant frequency of the longitudinal mode for the hollow watermelons (generally below or near to 160 Hz; Tables 2 and 4), explains this discriminating power.

Acknowledgements

The authors are grateful to Professor J. De Baerdemaeker (Agricultural Engineering Dept., K.U. Leuven, Belgium) for the technical support provided. This work was funded by grants from the *Comunidad de Madrid* and the Spanish Commission of Science and Technology (CICYT, project PETRI 95-0376-OP).

References

ABBOTT J.A., 1999. Quality measurement of fruits and vegetables. Postharvest Biol Tec 15, 207-225.

ABBOTT J.A., BACHMAN G.S., CHILDERS R.F., FITZGERALD J.V., MATUSIK F.J., 1968. Sonic techniques for measuring texture of fruits and vegetables. Food Technol 22, 635-646.

ABBOTT J.A, LILJEDAHL L.A., 1994. Relationship of sonic resonant frequency to compression test and Magness-Taylor firmness of apples during refrigerated storage. T ASAE 37(4), 1211-1215.

ANSYS Inc., 2003. ANSYS Users Manual. SAS IP, Inc.

ARMSTRONG P.R., STONE M.L., BRUSEWITZ G.H., 1997. Peach firmness determination using two different nondestructive vibrational sensing instruments. T ASAE 40(3), 699-703.

ARMSTRONG P.R., ZAPP H.R., BROWN G.K., 1990. Impulsive excitation of acoustic vibrations in apples for firmness determination. T ASAE 33(4), 1353-1359.

AVITABILE P., 2001. Experimental modal analysis. A simple non-mathematical presentation. Sound Vib (January), 1-11.

CHEN H., DE BAERDEMAEKER J., 1993a. Modal analysis of the dynamic behaviour of pineapples and its relation to fruit firmness. T ASAE 36(5), 1439-1444.

CHEN H., DE BAERDEMAEKER J., 1993b. Finite -element-based modal analysis of fruit firmness. T ASAE 36(6), 1827-1833.

CHEN H., DE BAERDEMAEKER J., BELLON V., 1996. Finite element study of the melon for nondestructive sensing of firmness. T ASAE 39(3), 1057-1065.

CHEN P., SUN Z., 1991. A review of non-destructive methods for quality evaluation and sorting of agricultural products. J Agr Eng Res 49, 85-98.

CLARK J.R., SHACKELFORD P.S., 1973. Resonance and optical properties of peaches as related to flesh firmness. T ASAE 16(6), 1140-1142.

COOKE J.R., 1972. An interpretation of the resonance behaviour of intact fruit and vegetables. T ASAE 15, 1075-1079.

COOKE J.R., RAND R.H., 1973. A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model. J Agr Eng Res 18, 141-157.

DE BELIE N., SCHOTTE S., LAMMERTYN J., NICOLAI B., DE BAERDEMAEKER J., 2000. Firmness changes of pear fruit before and after harvest with the acoustic impulse response technique. J Agr Eng Res 77(2), 183-191.

DIEZMA B., 2003. Detección no destructiva de problemas de calidad interna en sandías apirenas mediante respuesta acústica a impactos de baja intensidad. Doctoral Thesis. Universidad Politécnica de Madrid.

DIEZMA B., RUIZ-ALTISENT M., ORIHUEL B., 2002. Acoustic impulse response for detecting hollow heart in seedless watermelon. Acta Hort 599, 249-256.

DOSSING O., 1988. Structural testing. Part I. Mechanical mobility measurements. Naerum, Denmark: Brüel & Kjaer.

GARRET R.E., FURRY R.B., 1972. Velocity of sonic pulses in apples. T ASAE 15(4), 770-774.

HUARNG L., CHEN P., UPADHYAYA S., 1993. Determination of acoustic vibration modes in apples. T ASAE 36(5), 1423-1429.

JANCSÓK P., NICOLAI B., CLIJMANS L., DE BAERDEMAEKER J., 2001. Investigation of the effect of shape on the acoustic response of Conference pears by finite element modelling. Postharvest Biol Tec 23(1), 1-12.

STONE M.L., ARMSTRONG P.R., ZHANG X., BRUSEWITZ G.H., CHEN D.D., 1996. Watermelon maturity determination in the field using acoustic impulse impedance techniques. T ASAE 39(6), 2325-2330.

SUGIYAMA J., KATSURAI T., HONG J., KOYAMA H., MIKURIYA K., 1998. Melon ripeness monitoring by a portable firmness tester. T ASAE 41(1), 121-127.