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Firmness evaluation of melon using its vibration characteristic and finite element analysis*

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Abstract: The “Huang gua” melons were measured for their physical properties including firmness and static elastic modulus. The vibrational characteristics of fruits and vegetables are governed by their elastic modulus (firmness), mass, and geometry. Therefore, it is possible to evaluate firmness of fruits and vegetables based on their vibrational characteristics. Analysis of the vibration responses of a fruit is suggested for measuring elastic properties (Firmness) non-destructively. The impulse response method is often used to measure firmness of fruits. The fruit was excited using three types of balls (wooden, steel and rubber) and the vibration is detected by an accelerometer. The Instron device was used to measure the static elastic modulus of the inner, middle and outer portions of melon flesh. Finite element (FE) technique was used to determine the optimum excitation location of the chosen measurement sensor and to analyze the mode shape fruits. Four types of mode shapes (torsional or flexural mode shape, first-type, second-type spherical mode and breathing mode shape) were found. Finite element simulation results agreed well with experimental results. Correlation between the firmness and resonant frequency (r^2=0.91) and between the resonant frequency and stiffness factor (r^2=0.74) existed. The optimum location and suitable direction for excitation and response measurement on the fruit were suggested.

Key words: Melon, Sensing, Finite element, Experimental modal analysis, Firmness
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INTRODUCTION

Researchers continue to develop non-destructive methods to evaluate the effect of their impact on agricultural products using high-tech methods. Non-destructive techniques sensing has been applied for obtaining fruit and vegetable quality index. Non-destructive method for measuring firmness using sonic or vibration characteristics applied in previous investigations was recently reviewed by Armstrong (1989) and Liljedahl and Abbott (1994). The sonic vibration technique using the resonant frequency of the fruit vibration modes often applied to estimate fruit firmness had been verified to have high correlation to quality and maturity (Chen and Sun, 1991; Tollner *et al.*, 1993). Early researches found that f^2m or $f^2m^{2/3}\rho^{1/3}$ (f being the first or second natural frequency of the tested fruit, m being its mass, and ρ being density) could serve as the ‘stiffness coefficient’ or ‘index of firmness’ for fruits and vegetable of spherical shape (Abbott *et al.*, 1968; Finney, 1970; Cooke, 1972). The properties vibrations of some commodities are significantly correlated with firmness and ripeness (Essex and Finney, 1972). Acoustic

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properties of fresh fruits reported were applied in non-destructive quality evaluation (Ying and Cai, 1997). The acoustic emission was sensed by microphone and the signal was analyzed using an FFT (Fast Fourier Transform) algorithm to extract the response frequencies of the fruit. The result showed significant correlation between the acoustic parameters of apples and their apparent Young's modulus and firmness (Yamamoto and Haginuma, 1980). Theoretical analysis revealed two-fundamental mode shapes referred to as torsional modes and spherical modes which were found to exist in apples (Cooke, 1972; Rosenfeld *et al.*, 1991; 1993; Huarng *et al.*, 1992; Chen and De Baerdemacker, 1993a; 1993b; Chen, 1993).

The specific objectives of the work:

1. To determine the physical properties of melon.
2. To analyze the vibration of the mode shape by applying finite element model (FEM).
3. To establish the relationship between melon firmness, stiffness and resonant frequency.
4. To optimize the material of the impactor for detecting the melon.
5. To determine the optimum location of the excitation, to choose measurement sensor and to analyze the mode shape fruits.

MATERIALS AND METHODS

Materials

Thirty "Huang gua" melons of different weight were bought from a supermarket of Hangzhou for the study.

Impactor types

Three types of impactors, viz. wooden, rubber and steel, with the same diameter (30 mm) were used in the experiment.

Experimental determination of the spherical resonant frequency

The acoustic response of each melon which was suspended freely was measured by striking the fruit on the equator of its surface with different types of ball the output vibration on the opposite side of the fruit was detected by a made in China accelerometer (CA-YD-126) with sensitivity 0.30 pc/(m·s^2), cross-axis sensitivity ratio <5%, max acceleration (10^5 m/s^2).

The vibration detected by the accelerometer was transformed into electric signal, which was amplified and filtered by a 3−3000 Hz band processing circuit. The processed signal was sampled at a rate of 10 kHz with a data acquisition board PCL-1800 (Advantech Co. Ltd.). The signals were analyzed using a Fast Fourier Transform (FFT) to extract the resonance frequencies of the fruit. A schematic diagram showing the instrument setup for measuring the acoustic response of each melon is shown in Fig.1.

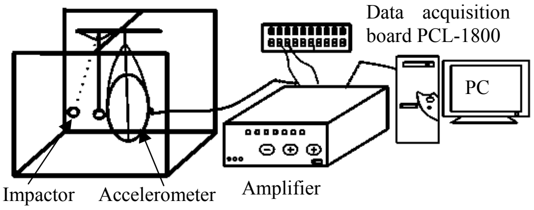

Fig.1 Schematic diagram of acoustic response measurement

An automated data acquisition system for the impact characteristic experiments of agricultural materials was developed. The software for the data acquisition was developed on the Advantech's Genie which is a Windows-based data acquisition, control, analysis and presentation development software package (Wang *et al.*, 2002). The schematic diagram of the acquisition system for impact characteristics and the structure of software of data acquisition are shown in Fig.2 and Fig.3 respectively.

Firmness measurement

The firmness of the melon was tested by parallel plate compression in a Universal Testing Machine

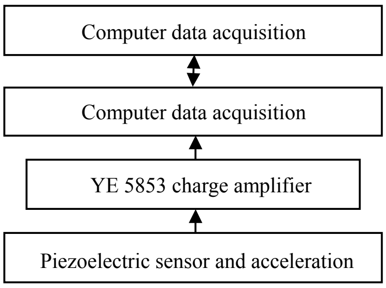

Fig.2 Schematic diagram of data acquisition system for impact characteristic

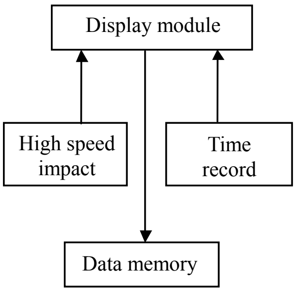

Fig.3 Structure of software of data acquisition system

(Instron Device 5543). The fruit positioned with their stem horizontal and compressed using 6 mm diameters puncture probe on the equator surface at the same location where the fruit was impacted at speed of 10 mm/s. The displacement curve was recorded.

The mass of the melon was measured with a precision balance. The volume was measured by the water method displacement. The melon was cut into halves and the dimensions of the principal axes were recorded (Fig.4). The bulk volume of each melon was estimated by the ellipsoid equation from Eq.(1). while the stiffness (S) was calculated by using Eq.(2).

$$V_{\text{est}}=1.334\pi ab^2 \tag{1}$$

$$S=f^2m^{2/3} \tag{2}$$

Eq.(2) was expressed in stiffness units with dimension 10^4 $\text{Hz}^2\text{g}^{2/3}$.

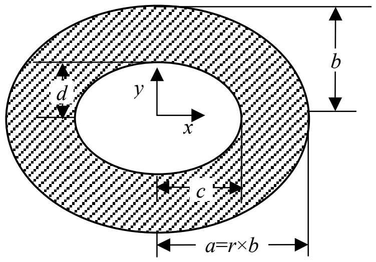

Fig.4 Dimension notations and coordinate system of melon

Experimental determination of static elastic modulus

Three cylindrical cores were cut near the equator from one half of each melon, using a cylindrical borer. Each cylindrical core was then cut into three 10 mm long 14 mm diameter samples referred to as outer, middle and inner layer of the flesh, Instron testing machine was used to measure the static elastic modulus. Compression speed of 25-mm/min was selected; the force deformation curve was obtained. Fig.5 shows a force-deformation curve measured at 10 mm-height the melon's middle layer. The curve appears linear in the initial compression phase and tended to be nonlinear after deforming about 4.5 mm. To calculate the static elastic modulus, the final linear part of the curve was used. At such a range of deformation, no juice was obviously squeezed out yet. Fig.6 shows the variation of young's modulus in the outer, middle and inner layers of the three samples.

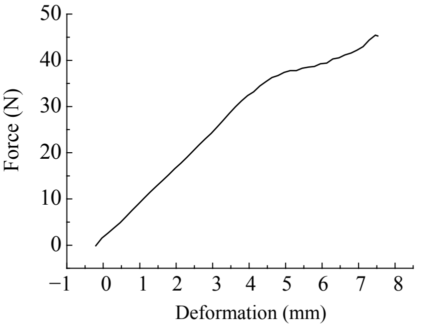

Fig.5 A force vs deformation curve from state compression test of a melon sample

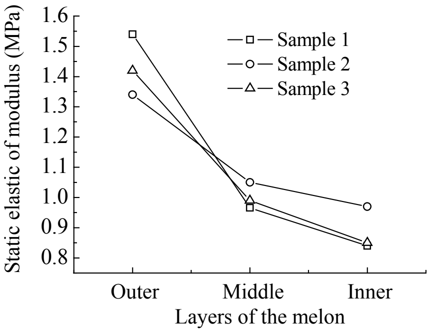

Fig.6 Show the variation of Young's modulus in three layers

Finite element simulation of the dynamic properties of intact melons

Finite element models of fruit were first created using ANSYS version 7.0 (SAS IP. Inc.). For the FE model, the melon was considered as an elastic body with a seed cavity. The nonlinear visco-elastic texture of the melon was therefore simplified as linear elastic texture. This simplification was widely used in previous theoretical study on the dynamic properties of the fruit (Cooke, 1972; Armstrong *et al.*, 1990; Rosenfeld *et al.*, 1991; Huarng *et al.*, 1992; Chen and De Baerdemacker, 1993a; 1993b). Good agreement with real fruit was obtained.

3-D 10-node 92 solid elements were used, allowing three translational and three rotational degrees of freedoms at each node. Model ellipsoidal solid was generated using some measuring experimental data in (Table 1).

The generated nodes were up to 610. Total nodes were calculated using subspace solver with free boundary conditions. The first six modes represented rigid body modes, and flexible modes started from the seven modes; the melon was aligned with the global coordinated system given in Fig.4. In this work the model updating technique was used to tune the lowest natural frequency *f* of each FE model to match that of the corresponding experiment. The modulus of elasticity (MOE) was then estimated without destroying the fruit used for dynamic MOE tests.

It is assumed that the system was not damped. The undamped vibration of the nodes was:

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t)+\boldsymbol{K}\boldsymbol{x}(t)=f(t) \tag{3}$$

where $\boldsymbol{M}$ is the mass matrix. $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{x}$ and $\ddot{\boldsymbol{x}}$ are the displacement and acceleration vectors, and t is the time.

In this Finite Element Modal Analysis (FEMA) free vibration is assumed. So no force is applied and correspondingly $f(t)$=0.

For linear system this vibration will be harmonic of the form:

Table 1 Physical geometrical and material properties of watermelons used in FE Model

Sample (No.)	$^1M_{\text{mea}}$ (kg)	$^2V_{\text{mea}}$ (cm^3)	$^3V_{\text{est}}$ (cm^3)	$^4V_{\text{flesh}}$ (cm^3)	$^5\rho$ (kg/m^3)	a (cm)	b (cm)	c (cm)	d (cm)	$^6E_{\text{est}}$ (MPa)
1	1.137	1210	1239	1011	1125	7.5	6.5	5.3	3.2	2.0
2	1.564	1669	1674	1304	1119	7.5	7.3	5.0	4.2	3.4
3	1.535	1550	1563	1207	1271	7.4	7.1	5.1	4.1	4.5
4	1.681	1790	1786	1337	1257	8.0	7.3	5.8	4.3	3.6
5	2.090	2110	2115	1268	1648	8.3	7.8	5.6	4.7	4.0
6	1.560	1666	1672	1170	1282	7.7	7.2	5.2	4.8	4.5
7	1.912	2040	2036	1399	1367	8.2	7.7	6.2	4.9	4.5
8	1.837	2200	2196	1477	1244	8.4	7.9	6.6	5.0	4.6
9	2.062	1949	1956	1367	1508	8.3	7.5	6.1	4.8	3.4
10	2.076	2150	2166	1523	1363	8.5	7.8	5.9	5.1	3.6
11	1.463	1595	1580	1252	1169	7.7	7.0	4.9	4.0	8.2
12	1.468	1560	1539	1214	1121	7.5	7.0	5.1	3.9	5.2
13	1.390	1538	1546	1340	1037	8.1	6.8	6.1	3.0	6.3
14	1.616	1840	1824	1366	1183	8.4	7.2	6.5	4.1	6.9
15	1.626	1720	1735	1354	1201	8.7	6.9	6.3	3.8	7.2
16	1.184	1510	1830	1191	994	8.2	7.3	6.1	5.0	4.3
17	1.433	1610	1595	1292	1109	8.0	6.9	5.9	3.5	8.0
18	1.575	1846	1830	1365	1154	8.2	7.3	6.3	4.2	5.8
19	1.537	1729	1718	1261	1219	7.7	7.3	5.4	4.5	6.6
20	1.621	1898	1808	1371	1574	8.1	7.3	6.2	4.1	4.9
21	1.312	1574	1565	1173	1220	7.9	6.9	5.7	3.8	7.6
22	1.393	1533	1541	1132	1231	7.3	7.1	6.3	4.1	5.8
23	1.456	1548	1539	1325	1099	7.5	7.0	5.3	3.1	6.9
24	1.477	1610	1585	1250	1182	7.3	7.2	5.0	4.0	6.1
25	1.310	1505	1455	1143	1146	7.3	6.9	4.9	3.9	7.3
26	1.177	1488	1413	1044	1127	7.3	6.8	5.0	4.2	4.8
27	1.219	1142	1116	1113	1095	7.2	6.8	4.9	3.7	6.7
28	1.500	1610	1621	1356	1110	9.3	6.5	6.7	3.1	7.3
29	1.031	1128	1244	1043	990	7.9	6.2	5.2	3.1	7.3
30	1.053	1150	1147	944	1120	8.0	5.9	5.2	3.1	4.9

$^1M_{\text{mea}}$: Measured mass; $^2V_{\text{mea}}$: Measured volume; $^3V_{\text{est}}$: Estimated volume; $^4V_{\text{flesh}}$: Flesh volume; $^5\rho$: Density; $^6E_{\text{est}}$: Estimated elasticity

$$X_i=\varphi_i\cos\omega_i t \quad (4)$$

where φ_i is the eigenvector representing the ith natural frequency, ω_i is the ith natural angular frequency and t is the time. By substituting Eq.(3) into Eq.(2) yields

$$(\boldsymbol{K}-\omega_i^2\boldsymbol{M})\varphi_i=0 \quad (5)$$

For a non-trivial solution this corresponds to the following equation.

$$(\boldsymbol{K}-\omega_i^2\boldsymbol{M})=0 \quad (6)$$

This equation represents an eigenvalue problem, which can be solved for n values of ω^2 (eigenvalues) and n eigenvector problems, where n is number of all the degrees of freedom (DOFs). This eigenvalue problem was solved by using ANSYS FE program using subspace iteration method.

RESULTS AND DISCUSSION

Mode shapes of the melon in vibration

This work took advantage of model updating technique to tune the lowest natural frequency of each FE model to match that of the corresponding experiment. The modulus of elasticity (MOE) was then estimated without destruction of the fruit for dynamic MOE tests. All estimated dynamic MOEs were comparable with reference data on melons (Chen *et al.*, 1996). It was reported that the dynamic MOEs were also about 2 to 10 times static MOE of melons (Deihl *et al.*, 1979). The MOE of FE model was tuned such that the first bending mode frequency matched experimental frequency (Cherng, 2000).

In the FE simulation, four kinds of mode shapes were obtained: first-type spherical mode, second-type spherical mode, torsional mode, and breathing mode.

1. First-type spherical mode

The first-type mode is the oblate-prolate mode. During vibration, the melon model extends in one direction and contracts at the same time in the perpendicular direction. Three such modes were found to exist within a narrow frequency band of 238.75 Hz to 279.22 Hz (Fig.7). For each first-type spherical mode, two nodal lines exist. In order to measure the vibration signal of the mode, excitation and response sensors should be placed on the melon surface far away from the nodal lines. Furthermore, the direction of both the excitation and the sensory axis of the response sensors should be in line with the vibration directions. The Y-axisymmetric mode has one nodal line in the upper part and another one in the lower part of the melon. Its vibration signal can be detected at the top, middle or bottom of the melon in the direction normal to the local surface. Most of the spherical modes measurements were made around the equator of the melon.

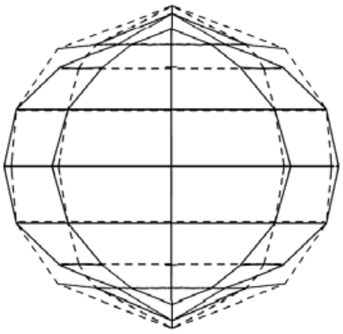

Fig.7 First-type mode

2. Second-type spherical mode

Fig.8 shows the second-type spherical modes with resonant frequencies (of 280.92 Hz to 288.92 Hz) characterized by the out of-phase transverse vibration at the upper and the lower part, little vibration along the longitudinal axis, existence of a nodal line each near the top, the equator, and the bottom.

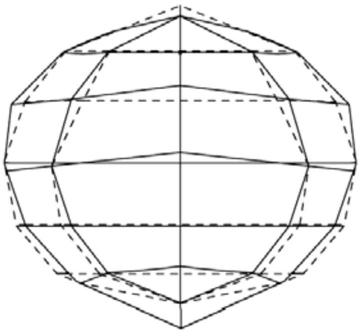

Fig.8 Second-type mode

3. Torsional mode

The torsional mode in Fig.9 has resonant frequency of 290.85 Hz to 296.33 Hz, and is characterized by opposite rotation of two hemispheres connected at the equator plane around the Y-axis; their vibration is normal to each other. Fig.9 shows the *Y*-axisymmetric torsional mode, with tangential displacement in planes vertical to the *Y*-axis. To measure its vibration signal, excitation and response sensors should be placed in the direction tangential to the upper or lower part of the melon where the most deformation occurs during vibration.

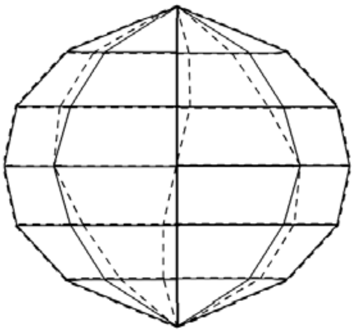

Fig.9 Torsional mode

4. Breathing mode

The breathing mode in Fig.10 is a pure compression mode with resonant frequency of 306.81 Hz, and characterized by simultaneous expansion or contraction in all radial directions. It is a kind of spherical mode with a node point in the center of the model. Its vibration signal can be measured anywhere on the surface in the radial direction.

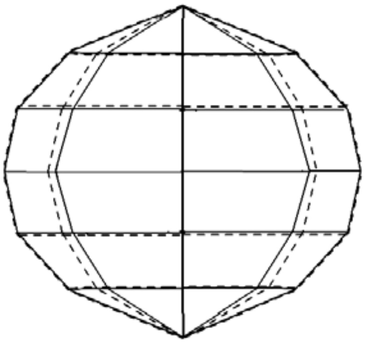

Fig.10 Breathing mode

Table 2 summarizes the results of experiment modal analysis. The results of finite element analysis on the selected melons were similar to these obtained by (Cherng, 2000; Chen *et al.*, 1996). There are six rigid body modes, which can be observed at 0 Hz.

Location and direction of force excitation and measurement sensors

The resonant frequency of some mode shapes obtained by experiment gives clues on the right locations and directions of the excitation and response measurement sensors. To measure the vibration signal of the mode, excitation and response sensors should be mounted in the region away from nodal lines. To estimate the firmness of the melon by the first-type longitudinal resonant frequency, the middle part of the melon surface is recommended as the location for the force excitation and the response sensors, because there are fewer modes that can be measured in this region. To measure its vibration signal, the excitation and response sensors should be placed in the direction tangential to the upper or lower part of the melon where most of deformation occurs during vibration. For the breathing mode, its vibration signal can be measured in the radial direction anywhere on the model surface.

Effect of testing fruit on the equator, with different types of impactor on the natural frequency

Fig.11 and Fig.12 show the frequencies versus amplitude curves for three types of impactors. The wooden ball shows the highest peak in the curve compared to the other two types.

Relation between the resonant frequency and melon stiffness factor (SF) and firmness

Linear regression analysis (LRA) of melon stiffness (*S*) and firmness yields the regression equation coefficient Y=205.25884+39.83976X and correlation r^2=91. Fig.13 and Table 3 give the relation between the firmness and resonant frequency. The

Table 2 Comparison between measured and estimated frequency

Sample No.	Measure frequency (Hz)	Identification modes	Estimated frequency or FE result (Hz)
1	238.75−279.22	First-type spherical mode	145.93−175.62
2	280.92−288.92	Second-type spherical mode	182.47−290.85
3	290.85−296.33	Torsional mode	293.34−298.75
4	306.81	Breathing mode	303.81

relation indicates the ability to accurately predict the fruit firmness as the quality in fruits and vegetables. Table 4 and Fig.14 show the relation between the resonant frequency and stiffness factor (SF) of the fruit, with regression equation coefficient Y=209.83092+6.53524X, correlation r^2=0.74.

CONCLUSION

The Finite Element Model (FEM) for melons was established by FE simulation. Three kinds of mode shapes referred to as the first-type spherical, second-type spherical mode, and the breathing or pure compression mode were found to exist for melon. The breathing mode was found to exist only in melon.

The simulation of mode shapes resonant frequencies agreed well with the measured values. The direct measured volume agreed well with the estimated volume, although there were some differences, which were within reasonable range, because there were some sources of errors attributed to the inherently imperfect geometry.

The smaller wooden ball 30 mm in diameter had higher amplitudes of higher resonant frequency.

The stiffness factor ($f^2m^{2/3}$) obtained by other

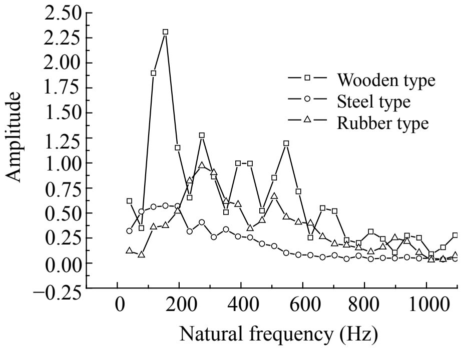

Fig.11 Shows the frequency vs highest amplitude curves (for three types of ball)

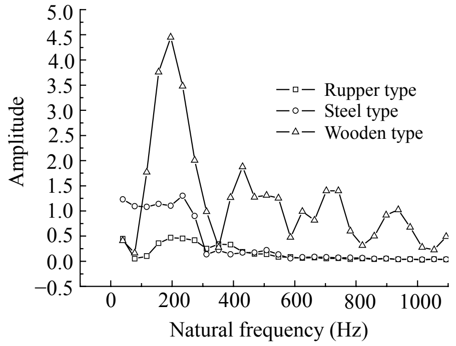

Fig.12 Shows the frequency vs highest amplitude curves (for three types of ball)

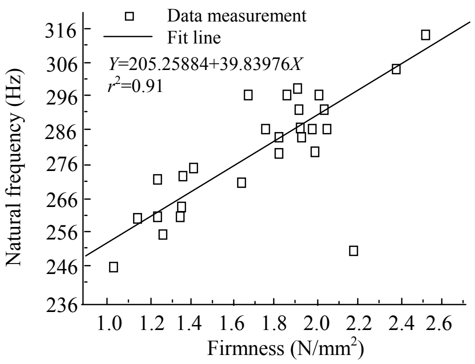

Fig.13 Relation between the firmness and natural frequency

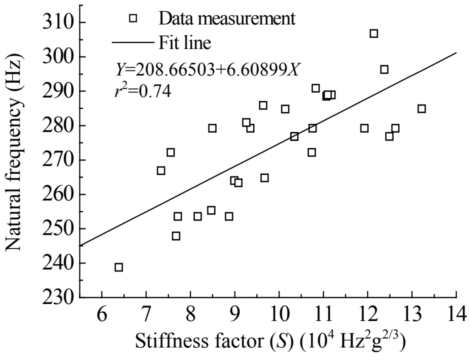

Fig.14 Relation between the stiffness factor and natural frequency

Table 3 Linear regression models for predicting firmness based on the resonant frequency

Parameter	Value	Error	Prob>|t|	R-square (COD)	Adj. R-square	Root-MSE (SD)	N
A	205.25884	3.51833	<0.0001	0.90596	0.9012	6.82804	30
B	39.83976	3.51833	<0.0001				

Table 4 Linear regression models for predicting stiffness factor based on the resonant frequency

Parameter	Value	Error	Prob>|t|	R-square (COD)	Adj. R-square	Root-MSE (SD)	N
A	208.66503	10.78405	<0.0001	0.75971	0.74437	10.26613	30
B	6.60899	1.06904	<0.0001				

researchers were also successfully used to evaluate fruit firmness so the stiffness factor has correlation with the resonant frequency, r^2=0.74. The firmness has better correlation (r^2=91) with the resonant frequency of the fruit.

The selection of location and direction for the force excitation and the response measurement sensor are most important for detecting a mode. The middle part on the fruit surface is suggested to be used while estimating the fruit firmness by the resonant frequency of the first-type spherical mode.

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