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Studies on the Nondestructive Measurement of Poisson's Ratio of Watermelon (I)
— Model Development —

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Introduction

A need for the objective characterization of the texture of fruits and vegetables has naturally led to a vigorous interest in techniques for measuring the well defined engineering properties of these biological tissues. The mechanical properties, nondestructive measurement of which is possible, can be used in such studies as in the following namely, the dynamics of fruit growth, the design and operation of harvesting and processing equipment and the retention of quality in the stored products.

Although numerous techniques for measuring the elastic properties of excised tissue have been reported, a nondestructive measurement technique for the shear modulus and poisson's ratio of the intact fruits and vegetables is still needed.

Free vibration data have been used to infer the internal structure of a lot of objects. Abbott, et al1). subjected intact apples to the periodic mechanical excitations as a nondestructive means for evaluating the textural quality. Each apple was suspended by its stem and was excited tangentially in the stem axis direction at the equator at a controlled frequency, varying from 20Hz to 4000Hz. The resonant frequencies were detected on the opposite cheek at about 20 degrees from the stem end. It was reported that apples subjected to vibrational excitation displayed a series of resonant frequencies; and that the second resonant frequency was associated with flexural vibrations, being strongly influenced by fruit size and the shear modulus. Chuma et al3). and Shiga et al7). examined vibrational characteristics of watermelons subjected to vibrational excitations. They indicated that the shear modulus was correlated with a coefficient, $f^2m^{2/3}$, where f and m were the natural resonant frequency and mass of the fruit, respectively. Yamamoto et al9,10). developed a nondestructive technique for measuring textural quality of apples and watermelons based on the acoustic response of the fruit. They obtained the natural frequencies of the intact fruit first by recording the sound to be produced out of the fruit tapped with a wooden ball pendulum, and then by performing Fourier transformation on the sound signal. They found that the natural frequencies for both apples and watermelons decreased with the storage time. Sasao8) measured vibrational characteristics in relation with the growth of watermelons and reported that the natural frequencies of watermelons decreased with the advancement of growth process. Armstrong et al2). measured the first resonant frequency of apples and used the pure compression mode of vibration of an elastic sphere model to predict the modulus of elasticity of the fruit. They found that the measured modulus of elasticity of fruit specimens, with the core included, correlated very well with the predicted elasticity for freshly picked 'Paula Red' and 'Golden Delicious' apples.

The above mentioned papers may well be regarded to have demonstrated a procedure by which the resonant frequency method can be used to find the shear modulus and elasticity modulus for the flesh of intact agricultural products having approximately spherical geometry. There have only been quite few studies about poisson's ratio of fruits and vegetables. Garrett et al[4]. detected the poisson's ratio of excised apples with velocity of sonic pulses and Hoki[5] examined the poisson's ratio of excised soybeans with ultrasonic. The difference in the velocity of propagation caused by the different boundary conditions of the two types of soybean specimen was used to determine the dynamic poisson's ratios. However, no report on poisson's ratio of intact agricultural products has appeared yet.

The objective of this research was, therefore, to investigate the vibrational behavior of intact watermelons caused by impact force using the simple elasticity expression model of vibration, and to try to develop a method by which the vibrational behavior can be used for indicating nondestructively, the poisson's ratio applicable for intact watermelons.

Materials and Methods

1. Materials

Watermelons used in this research were "TOKKOU" which were harvested from the area of Yamagawa, Kagoshima prefecture, Japan. Impact force responses were measured immediately after harvest. Then, sensing levels of the sample's flesh were evaluated subjectively by twenty researchers. The middle portion of each watermelon was sliced into testing pieces. At five levels, tooth sensation (TS) and water sensation (WS) were tested for the respective watermelon pieces. Here, three levels from the evaluation were fixed to be the 'value standard' of usual goods. Based on it, the worse ones had lower value, and the better ones had higher value.

2. Apparatus and Methods

Schematic diagram of the experimental apparatus is shown in Fig. 1. Pendulum device was used in the striking part of the experimental apparatus. The striking velocity could be changed by

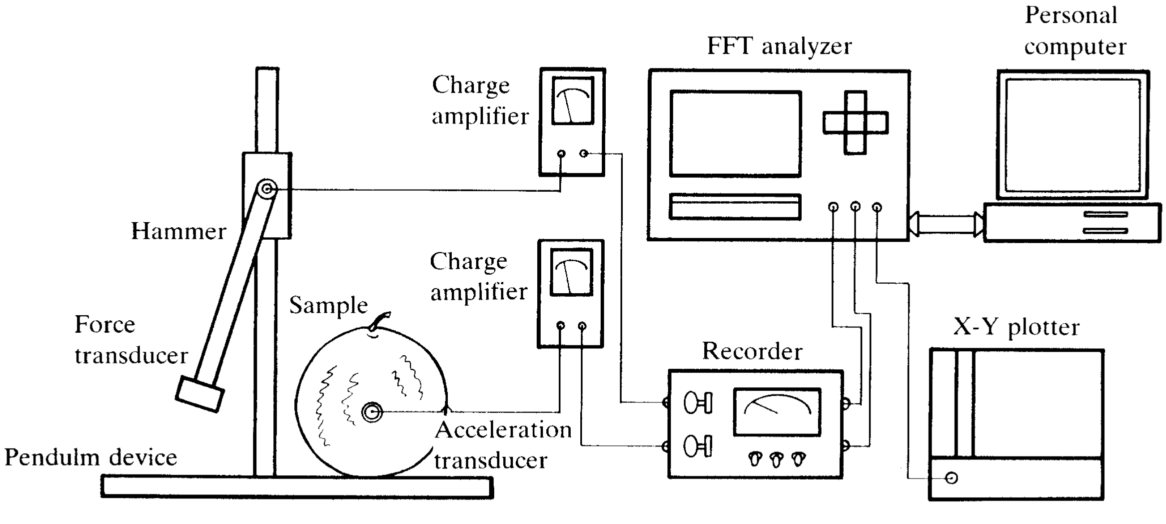

Fig. 1. Schematic diagram for experimental measurement.

changing the falling angle of the pendulum. The fulcrum of the pendulum could be adjusted up and down, so that it was very easy to make the striker, tap on the point of equator of each sample.

Samples were resting on the flat plate of pendulum device and the pendulum with a hammer was allowed to tap on equator of the samples from its predefined angle. The impact signals were measured by force transducer (RION PH-51) mounted in the hammer; and the vibrational signals caused by the impact forces were measured by an accelerated transducer (RION PV-95) kept on the sample's equator, separated by the predifined degrees, from the tapping point. These transducer outputs were amplified through two charge amplifier (RION NM-27) and were routed to a FFT analyzer (ONO SOKKI CF-920S) and then to a microcomputer (NEC, PC-9801). The FFT analyzer contained an AD converter capable of running at high speed. It also stored the resulting data in the internal memory, and the data were processed into a format usable for the computer.

After dividing the equator of the sample into twenty-four equal parts, vibrational signals were obtained at sixteen points shown as in Fig. 2. In order to obtain signals at sixteen points, the same striking point was chosen and the measurement point was changed sixteen times, because there was only one accelerated transducer. The measurement was repeated eight times at the same location, in order to reduce the error.

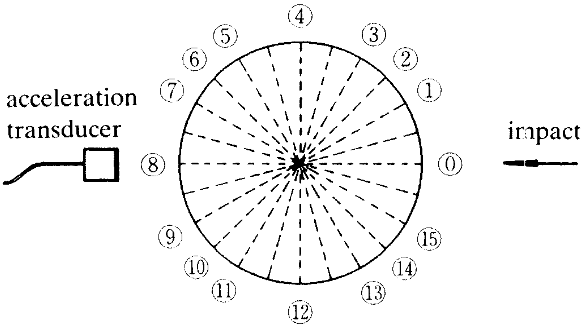

Fig. 2. Sketch picture for positions of impact and measurement.

Results and Discussion

1. Vibrational model

The free vibration of sample caused by an impact force was considered to be a vibrational behavior of a viscoelastic system of the spring and damping, with spring constant k and damping constant c, supporting a concentrated mass m. The vibrational approach of a point (Fig. 3) was given by

$$W_a = A_a e^{-\omega_0 h t} \sin\omega t \qquad (1)$$

where A_a = a constant,
e = radix base of the natural logarithm,
ω_0 = the natural frequency,
h = damping coefficient,

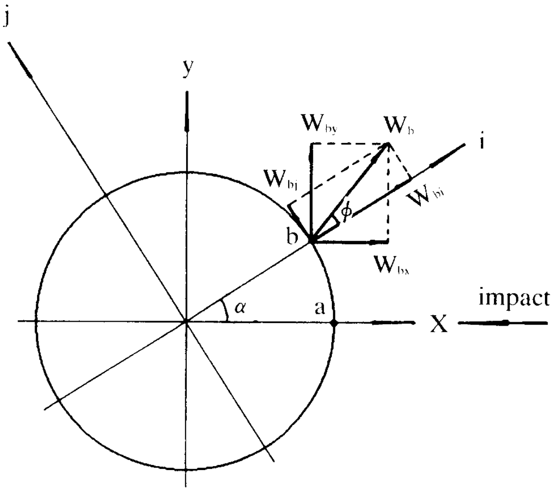

Fig. 3. Motion of point b with respect to x-y coordinates and i-j coordinates.

t = time,
ω = frequency.

Based on the following hypothesis that each cross section maintained permanent plane in vibration, the vibrational approach of b point for x axis direction was given by

$$W_{bx} = A_a e^{-\omega_0 ht} \sin\omega t \cdot \cos\alpha \tag{2}$$

If the poisson's ratio of the sample was μ, the vibrational approach of b point for y axis was given by

$$W_{by} = -\mu A_a e^{-\omega_0 ht} \sin\omega t \cdot \sin\alpha \tag{3}$$

Changing x-y coordinates to i-j dynamic coordinates, the vibrational approach of b point was given by

$$W_{bi} = A_a e^{-\omega_0 ht} \sin\omega t \cdot [\cos^2\alpha - \mu \sin^2\alpha] \tag{4}$$

$$W_{bj} = -A_a e^{-\omega_0 ht} \sin\omega t \cdot (1+\mu) \cdot \cos\alpha \cdot \sin\alpha \tag{5}$$

and combining the above mentioned two equations, the vibrational approach of b point was given by

$$W_b = A_a e^{-\omega_0 ht} \sqrt{\cos^2\alpha + \mu^2 \sin^2\alpha} \cdot \sin(\omega t - \phi) \tag{6}$$

where

$$\phi = \arctan\left(\frac{(1+\mu)\sin\alpha \cos\alpha}{\cos^2\alpha - \mu \sin^2\alpha}\right) \tag{7}$$

Equations (6) and (7) showed that the vibrational approach of point b and the difference of phase between point a and point b (lag angle) were related to the poisson's ratio μ and location angle α.

2. Lag angle

Substituting the poisson's ratio μ of 0.4 into equation (7), the relationship between lag angle ϕ and angle α was obtained. The solution is shown with the intermediate curve line in Fig. 4. As

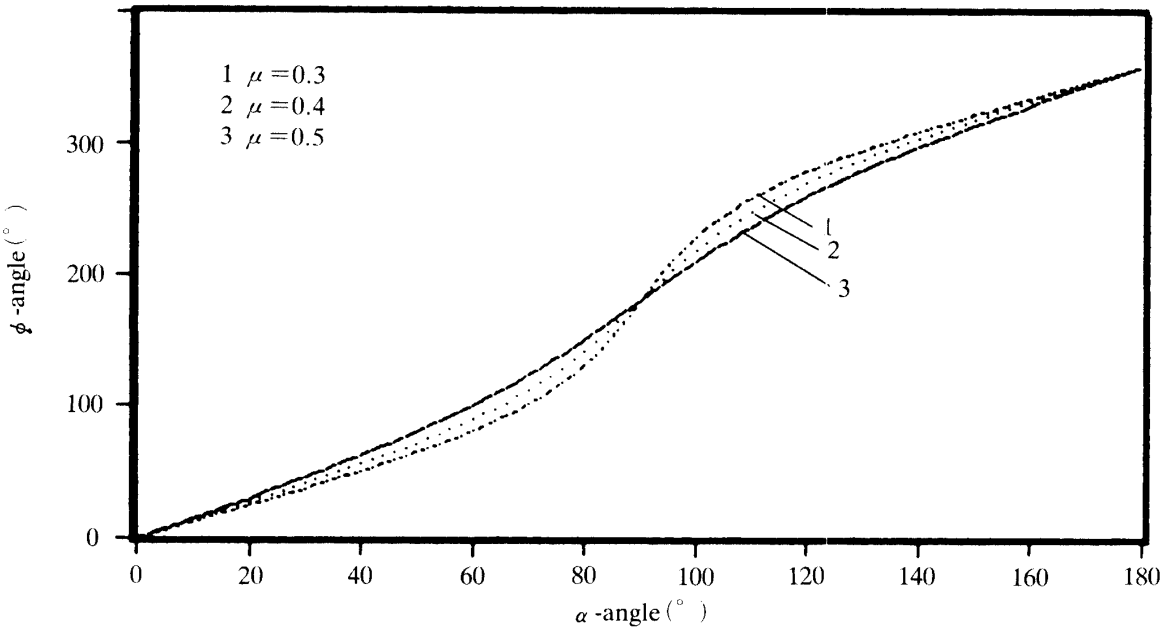

Fig. 4. Simulated ϕ-angle VS. α-angle for three watermelons with different poisson's ratio.

the angle α got increased, the lag angle ϕ got increased, too. When the angle α became 90 degrees, the lag angle ϕ became 180 degrees.

For the sample poisson's ratio μ counting greater than 0.4 (poisson's ratio μ is 0.5), the solution of the lag angle ϕ and angle α is shown by the 3-curve in Fig. 4. The same solutions for lower poisson's ratio (poisson's ratio μ is 0.3) are shown by the 1-curve in Fig. 4. These curves showed that the curve became flat as the sample poisson's ratio increased.

By using experimental apparatus, the actual values were measured in three samples having different sensing levels of tooth and almost the same water sensations (Fig. 5). Comparisons of the model solution with actual measurement of samples showed that the model curved lines nearly coincided with measured ones.

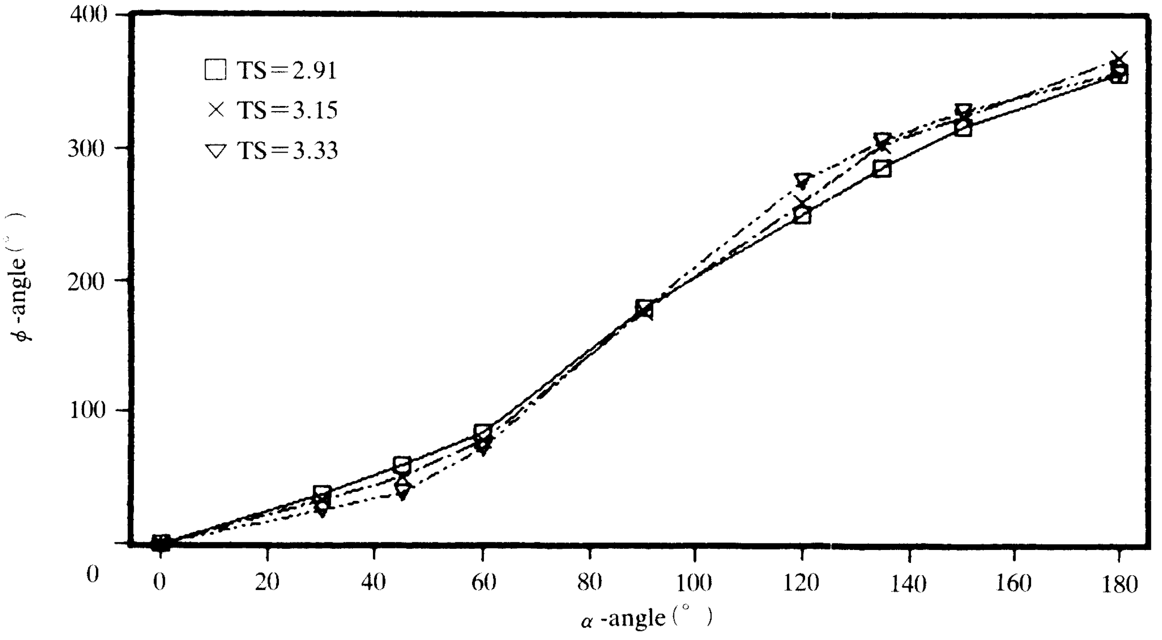

Fig. 5. Measured ϕ-angle VS. α-angle for three watermelons with different tooth sensations.

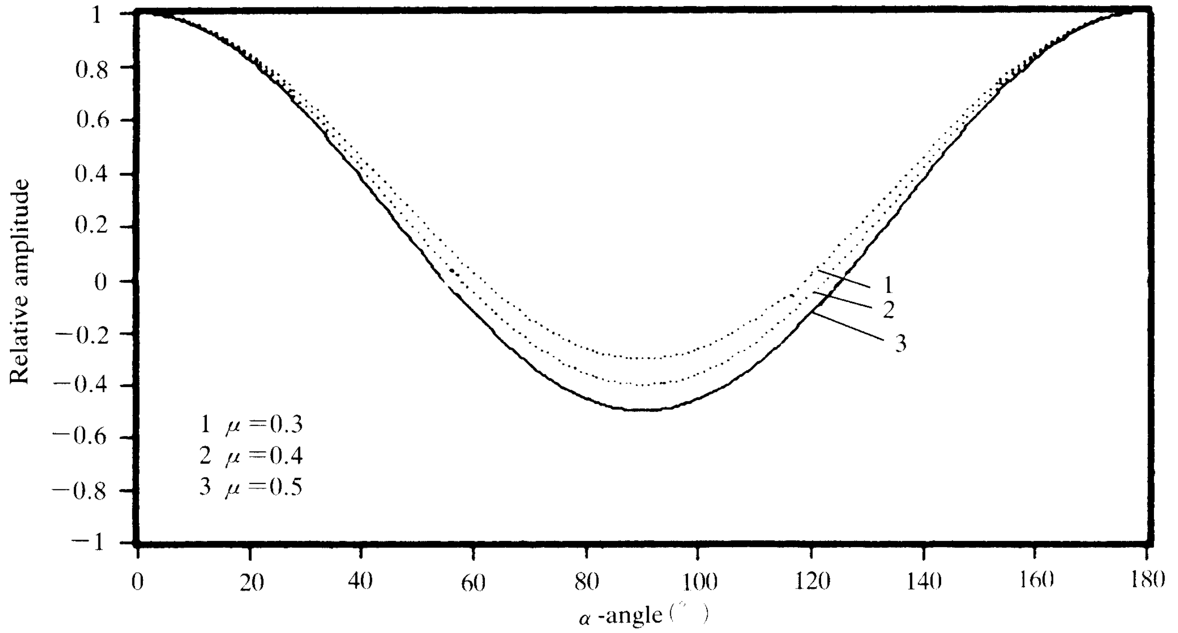

Fig. 6. Simulated relative amplitude VS. α-angle for three watermelons with different poisson's ratio

3. The maximum amplitude of vibration at i axis

The maximum amplitude of vibration at i axis, $A_a e^{-\omega_0 ht}[\cos^2\alpha-\mu\sin^2\alpha]$, was obtained from equation (4). In order to simplify the working processes, the $A_a e^{-\omega_0 ht}$ was assumed to be 1. Then, the maximum amplitude of vibration at i axis was determined with the poisson's ratio and angle α. Substituting the sample's poisson's ratio of 0.4 into equation (4), the relationship between the maximum amplitude of vibration and the angle α is described by the intermediate curve line in Fig. 6. As the angle α got increased, the maximum amplitude of vibration at i axis got

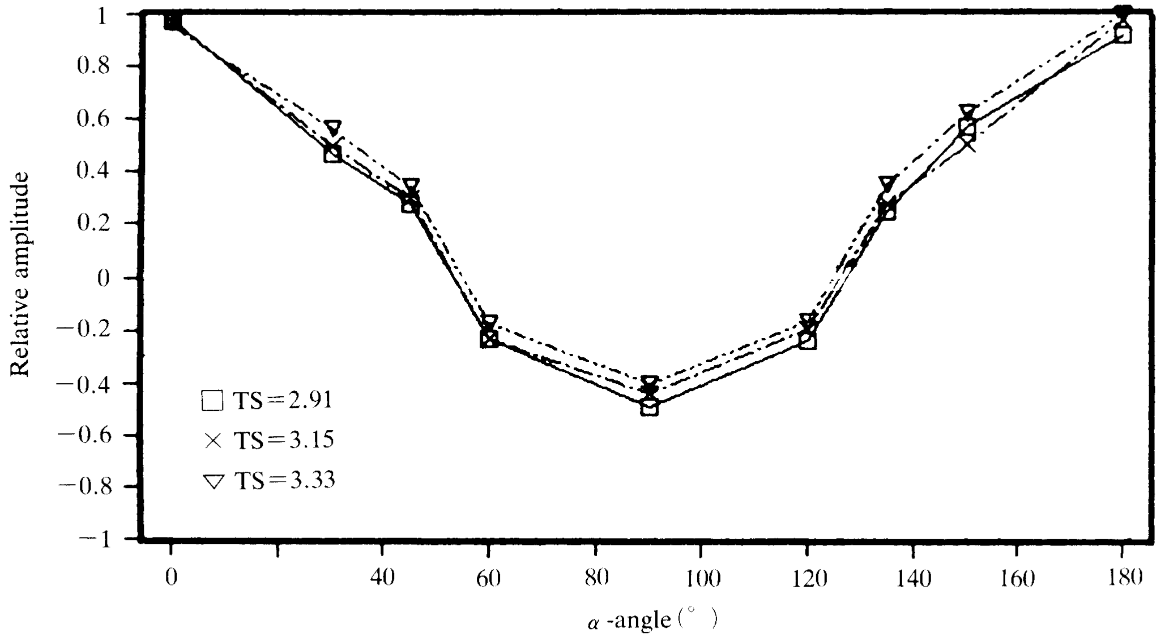

Fig. 7. Measured relative amplitude VS. α-angle for three watermelons with different tooth sensations

changed. When the angle α became 66.55 and 113.45 degrees, the amplitude of vibration at i axis became zero.

For the higher sample poisson's ratio μ (μ is 0.5), the solution of the maximum amplitude of vibration and angle α are described by lower curve as in Fig. 6. For lower poisson's ratio (μ is 0.3), the solution is described by the upper curve as in Fig. 6. As the sample poisson's ratio increased, the curve became sharp, and the angle α corresponding to zero amplitude of vibration at i axis became small.

By the same method, the actual values were measured for three samples having different sensing levels of tooth and almost the same water sensations (Fig. 7). Comparisons of the model solution with actual measurement of samples showed that the model curves coincided with the measured ones. Because the poisson's ratio of watermelon was almost determined with the fibrous tissue and water contents of watermelon[6]. Based on these results, therefore, the model was judged to be adequate for the interpretation of the vibrational behavior of intact watermelon caused by an impact force.

Summary

A simple elasticity model was used to simulate the vibration behavior of on intact watermelon caused by an impact force. The model results showed that the vibration behavior of equator of the intact watermelon was related with the poisson's ratio of watermelon. And it was possible to detect nondestructively the poisson's ratio of the intact watermelon.

In the experiment with intact watermelons, the vibrational signals were measured at the 16 points of equator of the watermelon. The measured vibration behavior at equator around the watermelon was in coincidence with the one simulated from the model. Therefore, the model was judged to be adequate for the interpretation of the vibrational behavior of the intact watermelon caused by an impact force.

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