可聴域の振動を使った果実硬度の非破壊計測法に関する研究

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Non-destructive measurement of fruit firmness by acoustic vibration

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One of the major determinants of fruit quality is internal texture. Texture is difficult to be objectively defined, but is increasingly important in quality assessment. Texture evaluation using traditional methods requires sampling of individual fruit, with limited usefulness because of the variation in maturity in bulk shipments and of that induced as a consequence of storage. Therefore more comprehensive non-destructive methods for product texture evaluation would have distinct advantages for quality control.

Several methods for non-destructive firmness measurement has been reported: (1) Resonance frequency, determined by subjecting fruit to vibration energy, has been related to firmness. (2) Analysis of the velocity of sound transmission. Here, the velocity of a sound impulse through fruit, delivered by a swinging pendulum, has been related to the firmness of muskmelon. (3) Analysis of ultrasonic wave transmission has also been used for evaluating physical qualities of agricultural products. It suggested that changes in ultrasonic sound velocity and attenuation could be used for the evaluation of firmness of biological materials.

In an effort to render the acoustic approach for non-destructive measurement of fruit firmness more practical, following experiments were conducted.

A non-destructive, acoustic method was applied to evaluate the firmness of nectarines (*Prunus persica* Batch.), apricots (*Prunus mume* Sieb. et Succ.), plums (*Prunus salicin*a Lindl.), and tomatoes (*Lycopersicon esculentum* Mill. 'Beiju'). Sound with frequencies from 200 to 2,000 Hz, generated by a miniature speaker attached to the fruit surface, was received by a small microphone attached to the opposite side. The signal was monitored by an oscilloscope. Sound frequency did not change during propagation in the fruit. However, as the microphone was moved along the circumference of the fruit, a phase shift in the received signal was observed. When the distance through which the microphone was displaced along the surface of the fruit corresponded to a shift of exactly one wavelength, the sound wavelength propagated within the fruit could be determined. The number of sound waves within the fruit over half its circumference was calculated as a function of this distance. Mature fruit propagated shorter wavelengths and consequently more of sound waves than immature fruit, indicating that the sound velocity in the mature fruit was lower than that in the immature fruit. The relatively simple method for measuring lower frequency suggests that the sound velocity propagated through fruit can be determined without measuring the absolute velocity.

A non-destructive acoustical measurement and an intrusive method for determining tissue firmness were compared to assess the textural properties of kiwifruit (*Actinidia deliciosa* (A. Chev.) Liang et Ferguson, 'Hayward'). Kiwifruit was treated with ethylene to initiate development and thereby provide a range of tissue

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textures. Individual fruit was subjected to pulsed sound, generated by a function synthesizer. The elapsed time for sound transmission through fruit tissues was measured by a storage oscilloscope (non-destructive method). It increased as function of the duration of ethylene treatment. Transverse slice of comparable kiwifruit tissue (2 cm in thickness) was placed on a stage and a conical probe attached to a load sensor was inserted to a depth of 5 mm. Tissue firmness was related to the maximum force required to achieve the constant strain (intrusive method). The results obtained by acoustical measurements were in good agreement with those achieved by the more conventional intrusive method, demonstrating that sound can be applied for the evaluation firmness in intact kiwifruit.

Ripening dependent changes in fruit texture and the development of physiological disorders affecting texture were perceived remotely from surface vibrations by Doppler laser detection. The technique was evaluated with range of different developmental stages representing normal texture development in kiwifruit ('Hayward') treated with ethylene. In addition, peach *(Prunus persica Batsch.*, 'Yahata Hakuhou') and Japanese pear (*Pyrus pyriforia Nakai*, 'Hosui') were evaluated at different maturity stages and citrus (*Citrus tamurana Hort.* ex Tanaka) selected for high quality was compared to fruit with the physiological disorder leading to granulation. Intact fruit was placed on a vibration generator stage and the sample was subjected to sine wave through a frequency series from 5 to 2,000 Hz. The attenuated vibration transmitted through the fruit to the top surface was precisely measured by the Doppler laser vibrometer coupled with signal enhancement by fast Fourier transformation. The phase shift caused by the transmission through the tissue was determined based on the difference between input and output vibration. Development of kiwifruit treated with ethylene result in suppression in phase shift as a function of maturation. The change was particularly significant in the range of 1,200 to 1,800 Hz. Transverse slices of ethylene treated kiwifruit were subjected to physical assessment of texture. A conical probe with a load sensor was inserted to a depth of 0.2 mm and the initial force (F_0) was used as a measure of the degree of firmness. The correlation between F_0 and phase shift at either 1,200 or 1,600 Hz was highly significant ($r = 0.81$-0.92). In peach and Japanese pear, the phase shift was also significantly altered as the maturation proceeded. In addition, distinctive phase shifts in citrus fruit allowed clear distinction between normal fruit and those afflicted with internal granulation. These data clearly show that Doppler laser detection of signals resulting from imposed vibration can be used as a versatile remote sensing tool for fruit tissue firmness and maturation evaluations. It also offers a means to evaluate otherwise concealed internal defects that render fruit undesirable.

To critically examine the feasibility of using a laser Doppler vibrometer (LDV) for fruit quality evaluation, measurements of firmness derived by this method were compared with those acquired through the use of a contact accelerometer. Fruit of the apple (*Malus pumila* Miller var. Domestica Schneider 'Fuji'), kiwifruit ('Hayward'), Japanese pear ('Nijusseiki') and Hassaku (*Citrus hassaku Hort.* ex Tanaka), were used. They were subjected to sine waves at frequencies from 5 to 2,000 Hz at the basal surface, and the vibrations resulting from these transmissions were precisely monitored at the upper surface with a LDV monitor. Measurements on all of the tested each fruit exhibited a distinct phase shift in the applied sine wave and in the resonance frequency, dependent on frequency used. These shifts were also detected by an accelerometer, but in this case the range of frequency was restricted to an upper limit of 400 Hz for kiwifruit, and 800 Hz for Japanese pear and Hassaku. Extending the range of frequency resulted in anomalous tissue behavior, most likely due to excessive compression of measured fruit surface by the attached accelerometer when the weight of accelerometer exceeded 1 g. Hence firmness measurements on the fruit depended on the phase shift and resonance frequency, and they were achieved with more precision with LDV than with the accelerometer. Moreover since LDV measurements can be made without directly contacting the fruit surface, there are distinct advantages in using this approach for remote sensing in quality evaluation.

Developmental changes in fruit texture during ripening were determined by remote sensing based on evaluation of surface vibrations using a Doppler laser detector. The technique was evaluated with fruit selected for having a range of firmness and textural characteristics. Kiwifruit ('Hayward') treated with ethylene, apple ('Ourei') stored at 10 °C or 20 °C and persimmon (*Diospyros kaki* L. 'Fuyu') stored at 10 °C. In each case fruit were placed on the stage of a vibration generator and the sample was stimulated by sine waves with a frequency ranging from 5 to 2,000 Hz. The vibration transmitted through the fruit to the top surface was precisely measured without contact by the Doppler laser vibrometer. The perceived signal was subtracted from the vibration of the stage, as measured by an accelerometer, yielding the true vibration signal at the top surface of the fruit. The phase shift was based on the difference between the input and output vibration. The phase shift significantly increased in the range of 1,200 to 1,600 Hz in all three kinds of fruit as a function of maturation. The resonance frequency, peak height, and peak width of second resonance peak were also determined. The resonance frequency decreased in all fruit, as maturation proceeded. In apple the peak height decreased as a function of storage duration, but in kiwifruit and persimmon the peak height fluctuated and it was not clearly to observe a consistent pattern. The amplitude of vibration decreased as a function of maturation when the imposed vibration was over 1,200 Hz. These data clearly show that the Doppler laser vibrometer detects the phase shift and vibration amplitude of fruits, and can be used as a versatile remote-sensing tool for determining fruit firmness and for evaluations of maturity.