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DETECTING HOLLOW HEARTS IN POTATOES USING NON-INVASIVE ACOUSTIC TECHNIQUES

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A b s t r a c t. Non-invesive method proposed by the author offers promises for the development of equipment that would sort potatoes with the hollow heart automatically.

K e y w o r d s: potato, hollow hearts, acoustic technique

INTRODUCTION

Rapid and objective measurement techniques of fruit and vegetable quality are needed to provide a top quality product to the consumer at minimum cost. Present grading techniques for fruits and vegetables are generally satisfactory, especially if one is primarily concerned with the external characteristics. Although external characteristics can be used to define the total quality of most fruits and vegetables, it would be beneficial to have techniques which can evaluate the quality of the total product to include the internal characteristics which are related to quality.

This paper reports on a study using ultrasonic techniques to detect hollow hearts in potatoes, a defect which is not visual externally but is highly undesirable.

LITERATURE REVIEW

There has been very little use of ultrasonic techniques for quality evaluation of fresh food products, especially for fruits and vegetables. Ultrasonic techniques have been used for determination of fat in beef [4,10] in pork [5], and in fish [3], but have not been used widely for fruits and vegetables. Fruits and vegetables are inherently very complex materials, in terms of both internal structure and geometric shape. The wave attenuation of these plant materials is very high due to the porosity nature of plant tissues. The potential of ultrasonic non-destructive evaluation of fruits and vegetables has been recognized for some time [6,9]. However, the very high attenuation of ultrasound by the plant tissues has limited studies to only thin samples. The difficulties caused by high attenuation may be overcome by using lower frequencies and by increasing the needed power of ultrasound, as long as it does not exceed the limit for cell and tissue damage.

Hollow heart in potatoes is a physiological disorder characterized by an irregularly shaped cavity in the center region of the tuber with a normal external appearance. Hollow heart is one of the major quality defects of potatoes and can cause serious economic losses to producers as well as processors. A non-destructive method of determining such internal disorder would make it possible to remove the defective tubers from a given lot of potatoes and thus improve the overall quality.

Several techniques have been developed for non-destructive detection and separation of potato tubers with hollow heart. These include use of tuber size or specific gravity [8], light transmittance [1], X-rays [2], and ultrasound. Detecting internal defects of potato tubers by using ultrasonic waves is a relatively new developing technique. Watts and Russell [11] used conventional ultrasonic test equipment on potatoes to evaluate the potential of using ultrasound to detect hollow heart in potatoes. The major problem they encountered with the ultrasonic system resulted from the high attenuation characteristics of the tissue making up the potato tuber, especially at high frequencies. The other problem they encountered included the requirement for an acoustic couplant, such as water or other wetting agent at the point of contact between the transducer and the potato. The difficulties encountered also dealt with the design of appropriate transducers and ultrasonic equipment. In spite of the problems, they expressed confidence that the method was feasible and could be made to work.

Ultrasonic techniques have potential advantages over other techniques including freedom from radiation hazards, which may appear in some of the existing non-destructive methods, such as X-rays, and ease of automating the food quality detection system. Ultrasonic techniques also have the advantage of relative low cost probes and associated electronics, a reasonably well-established theory between acoustic fields and material properties, indifference to hostile environments, and accessibility to materials opaque to light.

The objective of this study was to investigate and use ultrasonic techniques for detection of hollow hearts in potatoes, and to develop an objective ultrasonic measurement for evaluating the internal defects in potatoes.

INSTRUMENTATION

Preliminary experiments were conducted with tissue samples and whole products. This early phase of the study involved selection and re-evaluation of acoustic excitation and detection devices, coupling methods, proper frequency range, and signal analysis methods for detection of internal properties of agricultural products. The preliminary results led to the development of an ultrasonic, non-destructive evaluation system and signal analysis system for internal quality evaluation of potatoes as shown in Fig. 1. The basic setup of the systems included an Ultran BP 9400A high-power burst pulser, an Ultran BR 640A broadband receiver, a Tektronix 2232 digital storage oscilloscope, a pair of transducers, and a microcomputer system for data acquisition and analysis. The transducers were dry-coupling broadband transducers with a frequency of 250 kHz. These dry-coupling transducers can be placed directly on the test material surface for efficient ultrasonic energy transmission because a solid, compliant transitional layer (matching/protective layer) that was acoustically transparent was incorporated on the surface of the active piezoelectric element.

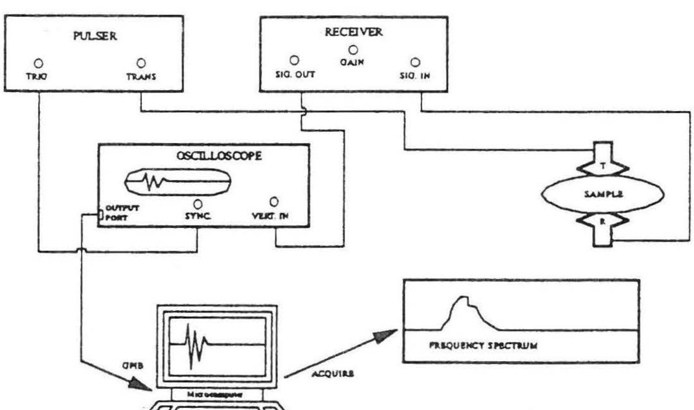

Fig. 1. Schematic diagram of the ultrasonic non-destructive evaluation system.

The system setup was in the through-transmission mode; i.e., the two transducers were placed on the opposite sides of a potato, one acting as a transmitter, the other one as a receiver. The electrical energy coming from the pulser caused the transducer to oscillate and launch a broadband ultrasonic pulse into the potato. The ultrasound traveled through the potato until it encountered a boundary or discontinuity. In such cases, a portion of ultrasonic energy was reflected. The transmitted ultrasound was received by another transducer, amplified and displayed on the oscilloscope screen, from which the time-of-flight (TOF) of the signal through the potato could be determined. The micro-computer-controlled serial interface GPIB allowed the capture of the signal from the digital oscilloscope to the computer and the data were stored on disks for further analysis. The signal analysis software used had a function to carry out frequency analysis of ultrasonic waves by means of the Fast Fourier Transform (FFT) techniques.

Results reported previously were limited to the studies of sample slices of fruits or vegetables due to the insufficient power of instrumentation and inappropriate transducers. However, with the experimental system described above, the ultrasound could be transmitted through whole potato tubers with the dry-coupling transducers. Therefore, ultrasonic non-destructive testing and evaluation (NDTE) were performed by studying the time and frequency domains of transmitted ultrasonic waves through tested potatoes. In addition to the ultrasonic measurement, an INSTRON Universal Testing Machine (Model 1123) was used to determine the modulus of elasticity of the acoustically tested potatoes.

EXPERIMENTAL PROCEDURES

'Atlantic' potatoes, provided by Midwest Potato Research Laboratory in Minnesota, were used in this study for hollow-heart detection. The potatoes were stored in a cold storage room before the tests at 2 °C and 90-95 % relative humidity. Forty-one potatoes were tested for internal quality evaluation using the ultrasonic measurement system.

Measurements for whole potatoes

Potatoes to be tested were removed from the storage room 24 h prior to the tests and allowed to reach room temperature. They were then numbered randomly, weighed, and their dimensions measured. The volume of a potato was determined using the platform scale method [7], and the density for the whole potato was determined. The potato was then tested by ultrasonic waves using the 250-kHz transducers. The potato was oriented so that the ultrasound passed through the shortest dimension of the potato. The transmitted ultrasonic signal through the potato was displayed on the digital oscilloscope. The digital data were then acquired by means of the microcomputer-controlled serial interface GPIB and saved on disks for further analysis.

After the ultrasonic measurement, the tested potato was cut open along the longitudinal axis, parallel to the flat side, and examined carefully for internal defects. The actual size of the hollow heart, if present, was characterized by measuring the two maximum cross-sectional dimensions and the total depth (the total depth was the sum of the maximum depth of the hollow heart measured on the two matching halves). Its volume was determined to the nearest 0.1 ml with water delivered from a 25-ml pyrex buret. Then cylindrical samples were taken from the tissue of the potato using a standard cork cutter to determine its ultrasonic velocities, modulus of elasticity, and tissue density. Both velocity and modulus of elasticity measurements were made along longitudinal and transverse directions of the potatoes.

Determination of ultrasonic velocities

A cylindrical sample 20.6 mm in diameter removed from the tissue of an acoustically tested potato was placed directly between the two transducers and aligned along the center line of the sample and the transducers. Measurements of time-of-flight (TOF) corresponding to the known distance traveled by ultrasonic signal was made from the Tektronix 2232, a 100-MHz digital storage oscilloscope. The cylindrical sample was serially shortened to the pre-determined thicknesses, and the TOFs for the sample at different thicknesses were measured. A simple linear regression method was used to determine ultrasonic velocity using the TOF information versus varying sample thicknesses. The average velocity of the sample under the investigation was equal to the inverse of the slope of the regression line.

Tissue density

Following the acoustic measurements, a cylindrical section of 20.6 mm in diameter was removed from the flesh of the acoustically tested potato and trimmed to a pre-determined length. The sample was weighed, its dimensions measured and its density calculated. Then the sample was used for modulus of elasticity measurement.

Modulus of elasticity

Biological materials such as potatoes usually do not satisfy the criteria for an elastic material. The modulus of elasticity for an elastic material is defined as the slope of a stress-strain curve for small strains and requires a complete recovery of strains upon removal of stress. However, it was difficult to determine the slope in this region of a stress-strain curve for potatoes because the curve was non-linear. The presence of moisture in the plant tissues offers little resistance to shear stresses causing relatively large deformations in response to small initial stresses. The curve shape is also affected by the non-parallel surfaces of the test sample and plastic deformation. For potato tissues, there is always some residual deformation remaining after the first loading and unloading cycles even for very small strains. Therefore, modulus of deformability or apparent elastic modulus (representative of the Young's modulus of elasticity for visco-elastic materials) was used to approximate the linear portion (slope) of the stress-strain curves obtained with the INSTRON universal testing machine without accounting for the changes in the ratio of stress to strain during unloading process. The words 'modulus of elasticity' and 'apparent Young's modulus' will be used interchangeably in this paper.

The cylindrical samples were used to determine the modulus of elasticity of the potatoes. The height of the sample was 20 mm. The cylindrical sample was compressed between the parallel compression plates at a rate of 20 mm/min. The force-deformation curve was plotted directly on a chart, and at the same time the data were sampled and captured by a microcomputer and stored on disks for calculation of modulus of elasticity.

RESULTS AND DISCUSSION

The physical and acoustical properties determined for the tested potatoes with and without hollow hearts are listed in Table 1 and Table 2, respectively. A hollow heart was usually found in the center of a potato tuber having a cavity with little discoloration of the surrounding tissue. The analysis of the transmitted ultrasonic signals through the whole potatoes was carried out in both time and frequency domain.

Time domain signal analysis

Figures 2 and 3 are plots of transmitted ultrasonic signals through a typical normal potato and one with hollow heart, respectively. As shown in the figures, the characteristics of transmitted ultrasonic signals through a normal potato and a hollow heart potato in time domain were obviously different. The transmitted ultrasonic signal through a hollow heart potato had longer duration time and more peaks and valleys than that through a normal potato. The reason for this might be that the ultrasonic signal bounced back

Table 1. Physical and acoustic properties of Atlantic potatoes with hollow heart

Potato number	Elastic modulus E_t (MPa)	E_l	Velocity V_t (m/s)	V_l	Potato volume (cm^3)	Cavity volume (cm^3)	Whole density (g/cm^3)	Tissue density (g/cm^3)	Path length (mm)	M_0 (V^2)
1	3.24	3.55	645.83	651.77	585	3.4	1.101	1.104	78.0	0.0154
3	3.08	3.30	559.14	626.71	563	3.5	1.103	1.113	74.1	0.0324
4	3.81	3.74	620.23	694.23	458	4.1	1.103	1.123	74.5	0.0216
5	3.91	4.23	763.33	721.49	386	4.8	1.098	1.114	69.5	0.0971
7	2.82	3.46	486.87	506.60	337	0.6	1.080	1.087	69.0	0.0216
8	2.78	3.44	657.90	643.69	725	5.7	1.094	1.105	85.4	0.0073
12	3.51	3.90	673.03	712.03	399	8.4	1.088	1.110	66.0	0.0820
14	4.18	4.02	745.18	819.45	513	20.1	1.058	1.105	72.7	0.0684
15	4.22	4.32	729.40	764.85	480	7.8	1.083	1.098	69.8	0.1060
17	3.56	3.58	605.68	684.72	639	3.8	1.097	1.102	82.1	0.0304
18	3.48	3.87	548.52	680.15	453	4.0	1.086	1.098	73.0	0.0526
20	3.54	3.78	723.95	758.48	368	6.3	1.092	1.104	72.6	0.0799
23	3.92	4.08	573.28	632.18	388	8.6	1.072	1.099	66.2	0.0330
24	3.43	4.11	679.36	704.03	325	3.7	1.098	1.098	72.1	0.1720
25	3.73	4.21	735.98	670.75	435	1.3	1.099	1.096	76.2	0.0903
26	3.08	3.65	706.11	726.94	392	1.8	1.105	1.107	70.1	0.0500
28	3.15	4.13	688.57	804.36	496	1.58	1.056	1.099	74.4	0.0555
30	3.45	4.08	660.75	698.54	543	1.8	1.088	1.113	71.0	0.0515
31	4.13	4.25	763.94	701.61	333	1.7	1.099	1.115	69.9	0.1980
32	3.80	3.71	595.82	636.60	276	5.4	1.080	1.085	64.2	0.0790
33	3.56	3.74	744.77	685.83	345	4.7	1.090	1.093	68.7	0.1090
35	4.22	4.56	738.73	735.80	347	3.8	1.104	1.110	57.2	0.1610
37	3.44	3.81	651.02	676.38	573	8.5	1.082	1.098	77.2	0.0106
38	3.54	3.68	628.90	694.07	352	4.8	1.091	1.113	65.2	0.0494
40	3.66	3.78	761.23	757.30	411	8.7	1.080	1.112	71.4	0.0827
41	3.51	4.21	686.42	714.03	352	2.1	1.108	1.112	66.8	0.0599
Avg	3.57	3.89	668.23	696.25	441		1.089	1.105	71.4	0.0696
SD	0.40	0.31	74.69	62.53	110		0.013	0.011	5.7	0.0487

E_t- modulus of elasticity measured along transverse direction of the potatoes; E_l - modulus of elasticity measured along longitudinal direction of the potatoes; V_t - velocity measured along transverse direction of the potatoes; V_l - velocity measured along longitudinal direction of the potatoes; Avg - average value; SD - standard deviation.

and forth in the hollow space existing in the potato. Therefore, one possible approach for separating the defective tubers from normal ones is to separate the tested potatoes based on the observed characteristics of the transmitted ultrasonic signals in time domain. In fact, all potatoes separated out by this ultrasonic technique were found to have hollow hearts with the cavity volume ranged from 0.6 to 20.1 cm^3 by cutting them open, as listed in Table 1, while no hollow hearts were found in the remaining potatoes. Therefore, this technique could be used for hollow heart detection in potatoes, and has the advantage of being capable of evaluating internal condition of potatoes which is difficult to evaluate from external appearance.

Frequency domain analysis

In spite of success of the aforementioned technique, it was difficult to establish a quantitative criteria for hollow heart detection merely based on the time domain signals. One possible solution to this problem is to use frequency spectrum analysis of the transmitted waves resulting from the ultrasonic pulse as affected by the hollow heart existing in potatoes. Figure 4 is a plot of the frequency amplitude spectra of the time-domain signals presented in Figs 2 and 3. The frequency

Table 2. Physical and acoustic properties of Atlantic potatoes with hollow heart

Potato number	Elastic modulus E_t (MPa)	Elastic modulus E_l (MPa)	Velocity V_t (m/s)	Velocity V_l (m/s)	Potato volume (cm^3)	Cavity volume (cm^3)	Whole density (g/cm^3)	Tissue density (g/cm^3)	Path length (mm)	M_0 (V^2)
2	3.28	3.54	635.05	649.11	262	0.0	1.111	1.111	61.1	0.5570
6	2.90	3.22	577.49	626.28	342	0.0	1.105	1.106	65.7	0.4380
9	3.01	3.29	684.78	682.39	402	0.0	1.112	1.118	76.8	0.3450
10	3.13	3.00	518.77	613.05	282	0.0	1.096	1.082	64.7	0.5230
11	3.25	3.46	637.37	611.64	393	0.0	1.109	1.095	71.3	0.5110
13	3.07	3.75	639.01	643.87	482	0.0	1.108	1.101	76.5	0.2770
16	3.44	3.67	554.51	561.65	550	0.0	1.085	1.083	77.0	0.7210
19	3.54	3.71	589.69	658.38	469	0.0	1.102	1.116	76.0	0.7660
21	3.36	3.77	661.02	643.82	352	0.0	1.105	1.107	69.3	0.7050
22	3.72	4.07	798.85	800.32	351	0.0	1.108	1.115	71.5	1.0300
27	3.40	3.69	747.87	714.83	642	0.0	1.097	1.115	89.7	0.6590
29	4.29	4.70	740.24	772.72	414	0.0	1.109	1.111	76.2	0.8620
34	4.33	4.17	755.24	710.86	684	0.0	1.098	1.094	85.4	1.0260
36	3.50	3.39	582.23	596.72	590	0.0	1.092	1.101	79.1	0.2890
39	3.47	3.90	578.50	654.29	453	0.0	1.104	1.107	74.3	0.4620
Avg	3.44	3.69	646.71	662.66	444		1.103	1.104	74.31	0.6114
SD	0.41	0.42	82.48	64.60	126		0.008	1.013	7.51	0.2415

Explanations as in Table 1.

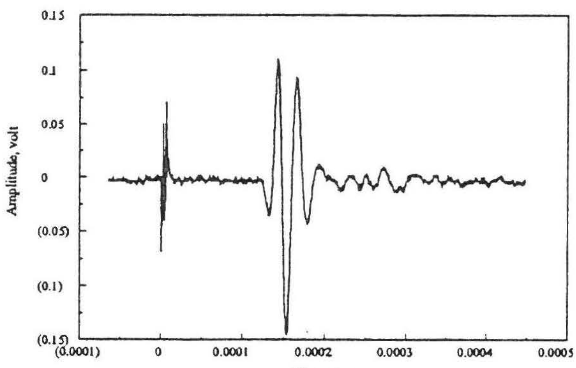

Fig. 2. Transmitted ultrasonic signal through a normal potato.

amplitude spectra were obtained by means of FFT techniques with a window size of 250 s starting from the leading edge of the transmitted signals. The signal amplitude of transmitted ultrasonic frequency components through the hollow heart potato was much less than that through the normal one. The frequency spectrum for the normal potato tended to be a smooth envelope, while that for the hollow heart potato has more maxima and minima due to the reflection and interference of sound waves within the potato. However, the peak frequency for each tested potato changed from one to another, no matter whether there existed hollow heart or not. The peak frequencies are usually affected by the mass and the physical properties of the tested potatoes. The large variations existed among the potatoes

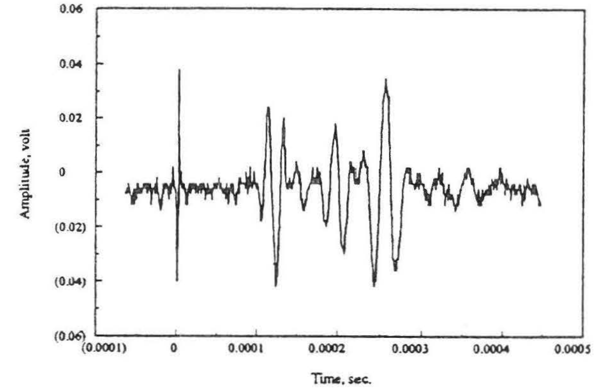

Fig. 3. Transmitted ultrasonic signal through a hollow heart potato.

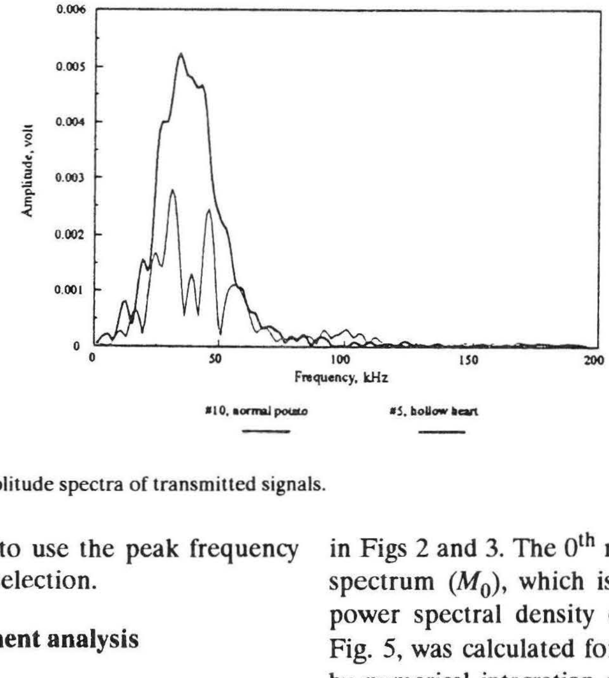

Fig. 4. Frequency amplitude spectra of transmitted signals.

made it difficult to use the peak frequency for hollow heart selection.

Spectral moment analysis

Ultrasonic measurements for the potatoes were quantified by applying a signal analysis method based on power spectral moments. The energy content distributed over the frequency bandwidth, generally referred to as power spectrum of the signal, was obtained using the FFT techniques. The windows used for carrying out the FFT was started from the leading edge of transmitted signals with duration of 250 s. Figure 5 is a plot of power spectra of the time-domain signals presented in Figs 2 and 3. The 0^{th} moment of a power spectrum (M_0), which is the area under a power spectral density curve as shown in Fig. 5, was calculated for each tested potato by numerical integration method. The spectral moment M_0 represents the amount of ultrasonic power transmitted through a tested potato. Therefore, the ultrasonic measurement for hollow heart detection was quantified in terms of the amount of power transmitted through a whole potato. The calculated M_0's for all the tested potatoes are listed in Tables 1 and 2. The tables showed that the normal potatoes had much greater spectral moment values than the hollow

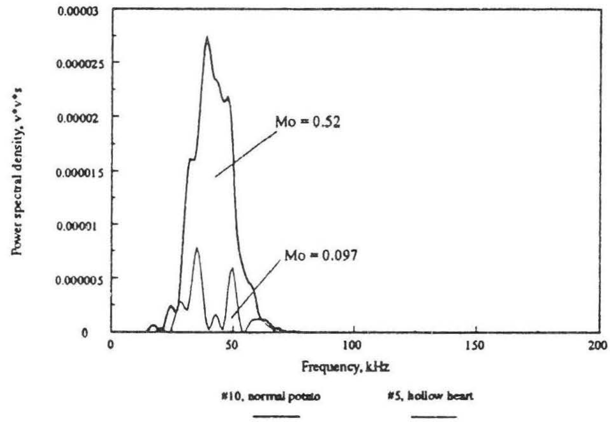

Fig. 5. Comparison of power spectra of normal and hollow heart potatoes.

heart potatoes. There was a distinct separation between the normal potatoes and hollow heart potatoes.

DISCUSSION

Figures 6 and 7 are the plots of M_0 versus volume of the potatoes and wave path length of the potatoes, respectively. Potatoes with hollow hearts transmitted much less ultrasonic power than those of normal potatoes. Under the instrument setting conditions of the experiment for detecting hollow hearts in 'Atlantic' potatoes, when M_0 was greater than 0.2 for a tested potato, as shown in Figs 6 and 7, there was no hollow heart found in the potato. On the other hand, when M_0 was less than 0.2, hollow hearts were found in the tested potatoes. Therefore, the parameter M_0 could provide an effective method of analyzing the ultrasonic measurements for quantitative, non-invasive evaluation of hollow hearts in potatoes.

Bigger potatoes had larger dimensions and hence more attenuation of the signal. It was expected that M_0 values for bigger potatoes would be lower than that for smaller potatoes, since less ultrasonic power could pass through the bigger ones. However, the

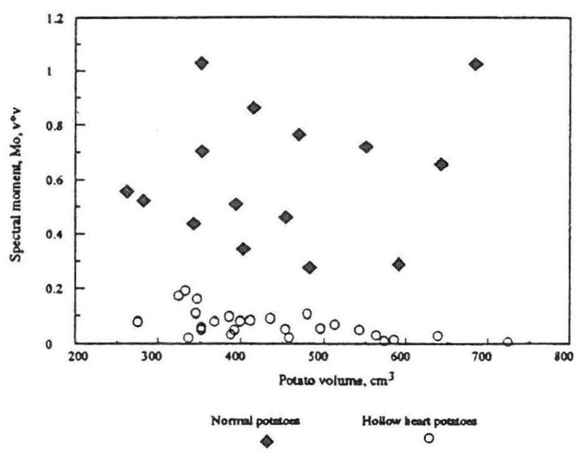

Fig. 6. Power spectral moment vs potato volume.

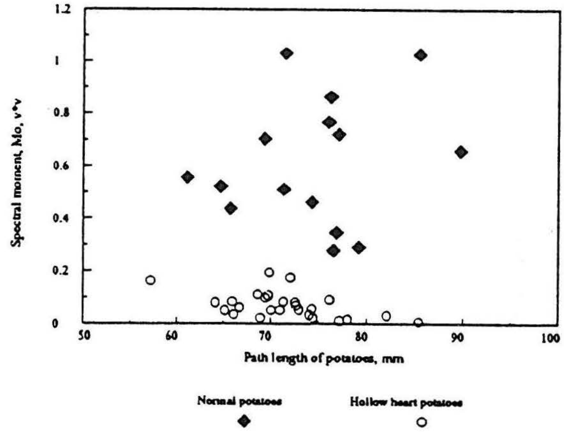

Fig. 7. Power spectral moment vs path length of potatoes.

results indicated that there was no relation between the path length or size of potatoes and M_0, as shown in Figs 6 and 7. The reason for this may be that the coupling conditions of the transducers to a whole potato were inconsistent due to the non-uniform shapes of the potatoes. When the transducers were not in perfect contact with the surface of a potato, less ultrasonic power would be transmitted into the potato, regardless of the potato size. This problem may be solved by using some coupling materials, such as coupling gels, on the surface of potatoes in addition to the dry coupling method to ensure the coupling consistency for each measurement. However, the amount of ultrasonic power transmitted through a potato was more affected by the presence of hollow heart than the inconsistent coupling condition, as indicated by Figs 6 and 7. Nevertheless, improvement of the coupling condition may further improve the accuracy of this technique.

Figure 8 is a plot of measured density for a whole potato and the observed cavity volume. It can be seen that the correlation between the density and cavity size of the potatoes was only fair (r=0.811). The measured density generally decreased as the volume of a hollow heart increased. However, due to the large variations of the data, it would be difficult to establish a criteria for detection of hollow hearts in potatoes based on the density measurements. The accuracy would be too low to permit its use as a grading technique.

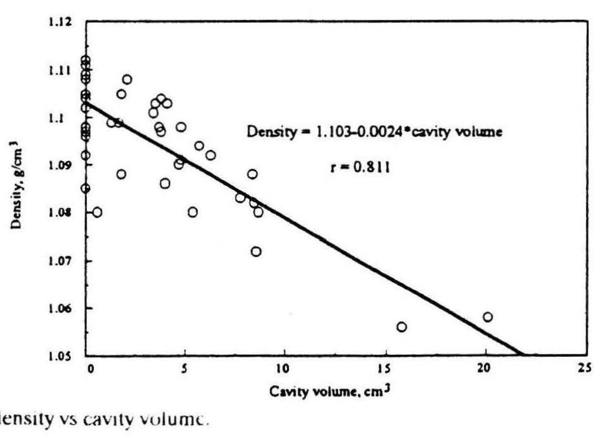

Fig. 8. Whole potato density vs cavity volume.

In spite of the density differences of the whole potatoes, there was no difference found between the tissue densities of normal potatoes and hollow heart potatoes, as shown in Tables 1 and 2. Furthermore, there were no significant differences between the ultrasonic velocities, as well as the moduli of elasticity, measured from the tissues of normal potatoes and hollow heart potatoes. This suggested that physical and acoustical properties were approximately the same among these potatoes, regardless whether there existed a hollow heart in a potato or not.

The results of the investigation of 'Atlantic' potatoes showed that the waveform of transmitted ultrasonic signals through a hollow heart potato differed from that of a normal potato. Further, the defective potatoes could be separated on the basis of power spectral moment of the transmitted ultrasonic signals. Therefore, it was concluded that this non-invasive method could be used to identify internal quality of potatoes that are difficult to evaluate from external appearance. Such a measurement offers promises for the development of equipment that would sort potatoes with the hollow heart automatically.

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