聖護院ダイコンの動的粘弾性及び音響特性

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Dynamic Viscoelastic Properties and Acoustic Properties of Japanese Radish (Shogoin) Roots

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The dynamic viscoelastic properties of Japanese radish roots and the natural frequencies of intact Japanese radish roots were measured by forced vibration methods and the acoustic impulse response method respectively. The dynamic Young's modulus showed a positive and significant relationship with the nondestructive index including the natural frequency. (Received Oct. 25, 1983)

Dynamic viscoelastic properties and acoustic properties of apples and watermelons were measured and the relation between the dynamic Young's modulus (E') of flesh and the natural frequencies of intact sample were examined in previous papers[1,2,3,4]. It was reported that E value of flesh specimen measured by the vibrating reed method and E' value calculated from the natural frequency of an intact sample coincide within an order of magnitude. This suggested the validity of the acoustic impulse response method for nondestructive internal quality evaluation of apples and watermelons.

In this paper, as an application of this nondestructive method to other agricultural products, dynamic viscoelastic properties and acoustic properties of spherical Japanese radish (Shogoin) roots were measured. The complex elastic modulus ($E^*=E'+iE''$, E'': loss modulus) of a Japanese radish root specimen was measured by the vibrating reed method and an apparatus for rapid and easy measurement of dynamic viscoelasticity for gel-like materials. The natural frequencies of an intact Japanese radish root were measured by the acoustic impulse response method. The relations between the dynamic Young's moduli of Japanese radish roots and the natural frequencies of intact Japanese radish roots were examined.

MATERIALS AND METHODS

1. Test samples

The cultivar of Japanese radish root samples used in this study was Shogoin (Hayabutori Shogoin Daikon). This cultivar was chosen from its spherical shape. The Japanese radish seeds were sown in early September 1982 and 1983. They were grown under commercial cultural conditions in Yagihashi, Yatabe-machi Ibaraki-ken. Samples tested in 1982 were harvested on October 22, November 8 and November 17. On each date of harvest, 15, 15, and 15 samples were used for expreiments respectively (total 45 samples). Samples tested in 1983 were harvested on October 17, October 27, November 8, November 21 and December 6. On each date of harvest, 6, 7, 10, 10 and 7 samples were used for experiments respectively (total 40 samples). After harvest, leaves were cut away and test samples were stored at 5°C. Nondestructive measurements (mass(m), density(ρ) and acoustic properties) were made within 3 days after harvest. Destructive tests were done within 7 days after harvest.

2. Measuring method of natural frequency

Measuring method of the natural frequency from impact sound is almost the same as described in the previous paper[1]. From the impact sound, the power spectrum was calculated by means of a fast Fourier transform (FFT). The blocksize of data was 2048 and sampling interval was 2×10^{-4}sec for the calculation. Thus the power spectrum in the frequency range from DC to 2500Hz with frequency resolution of 2.44Hz was obtained. After the reliability of the peak frequencies of the power spectrum was confirmed, these peak frequencies were taken as the natural frequencies.

3. Measuring method of complex elastic modulus

E' and E'' of Japanese radish roots were measured by an apparatus[5] for rapid and easy measurement of dynamic viscoelasticity for gel-like materials (Toyo Seiki Seisaku-sho Co., Rheolograph CV-100). Both the upper and lower ends of a cylindrical root specimen (10mm in diameter and 30mm in height) were attached to plates of this apparatus. The lower end was forced to vibrate in longitudinal direction (sinusoidal wave of 2.5Hz in frequency and 2mm$_{p\text{-}p}$ in amplitude). The stress at the upper end was measured by a load cell. From the stress amplitude and the phase difference between stress of the upper end and displacement of the lower end, E' and E'' were calculated by analog circuit and represented in two analog meters. For samples tested in 1983, only E' value was measured since the meter indicating E'' value was unstable and it was hard to measure reliable E'' value. For samples harvested on November 8 and November 17, 1982 and samples tested in 1983, the vibrating reed method[2] was also used for measurement of E' and E''. The complex elastic modulus $E^*=E'+iE''$ measured by the vibrating reed method and Rheolograph will be designated $E_v^*=E'_v+iE''_v$ and $E_r^*=E'_r+iE''_r$ respectively in this paper.

4. Compression test

Constant speed uniaxial compression test was done for a cylindrical root specimen (20mm in diameter and 20mm in height). From the force-deformation curve of constant speed (10mm/min) uniaxial compression test by a plate, apparent Young's modulus ($\dot{E}'_{app}$), breaking stress and breaking strain were calculated by the same way as the previous paper[6]. Energy required till breaking point (area under the force deformation curve till breaking point) was also calculated and designated breaking energy.

RESULTS AND DISCUSSION

For each sample, two methods of impact sound mea-

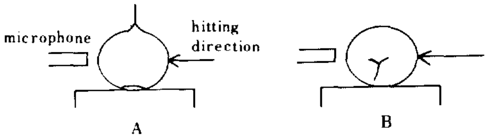

Fig. 1. Two methods(A and B) of impact sound measurement for a Japanese radish(Shogoin) root.

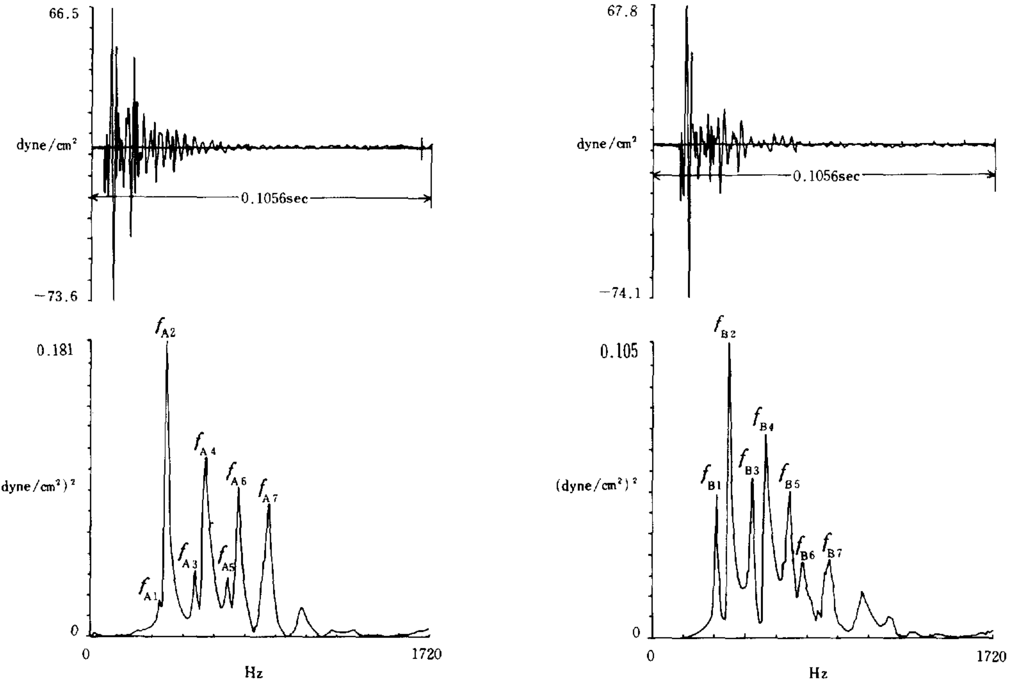

Fig. 2. Typical impact sound waves (upper) and their power spectra(lower) of a Japanese radish(Shogoin) root by the measuring method A(left) and B(right).

$f_{A1}=351.4$Hz
$f_{A2}=383.1$Hz
$f_{A3}=529.5$Hz
$f_{A4}=583.2$Hz

$f_{B1}=331.8$Hz
$f_{B2}=400.2$Hz
$f_{B3}=514.8$Hz
$f_{B4}=583.2$Hz

surement, A (the point of a root is directed upward) and B (the point of a root is directed sideward) as shown in Fig. 1 were made. Typical impact sound waves of a Japanese radish (Shogoin) root and their power spectra are shown in Fig. 2. Peak frequencies of the power spectrum by the measuring methods A and B were designated f_{A1}, f_{A2}, f_{A3}, … in sequence and f_{B1}, f_{B2}, f_{B3}, … in sequence respectively. The reliability of the peak frequencies of power spectra was tested by examining the difference between f_{Ai} and f_{Bi}. There was a tendency for some samples that f_{A1} and f_{B2} were slightly difficult to appear in the power spectrum. However for most samples, the differences between f_{Ai} and f_{Bi} (i=1,2,3,4 for 1982 samples, i=1,2 for 1983 samples) were less than 20Hz (Fig. 3). The average of f_{Ai} and f_{Bi} was designated f_i and used as the natural frequency in the analysis to be described later. For samples tested in 1982, f_1, f_2, and f_3 ranged from 250 to 440Hz, from 270 to 500Hz and from 390 to 720Hz respectively and showed negative correlation with sample mass (Fig. 4).

The mean values and standard deviations of nondestructive and destructive quality parameters for samples tested in 1982 and 1983 are summarized in Table 1 and 2 respectively.

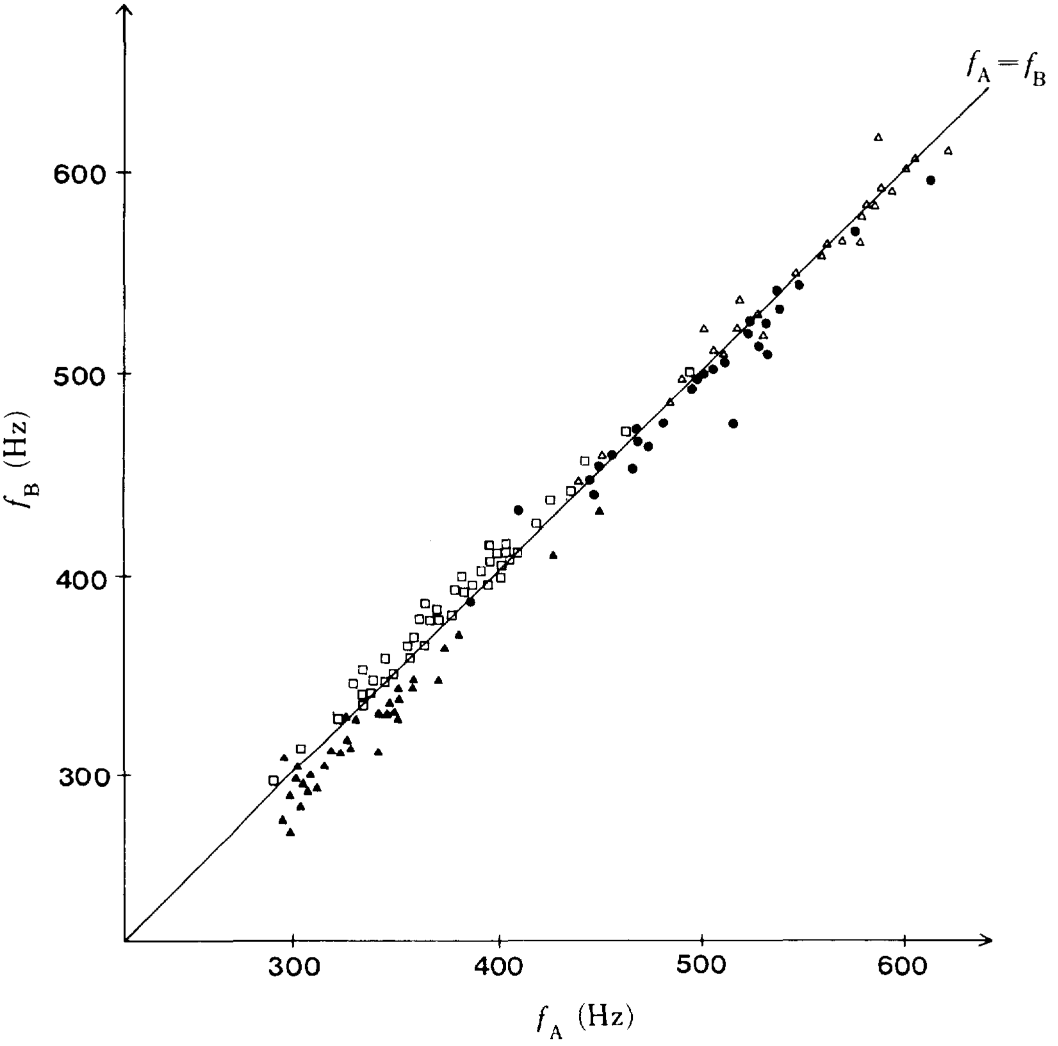

Fig. 3. Relations between f_{Ai} and f_{Bi} for 1982 samples

▲ …… f_1
● …… f_3
□ …… f_2
△ …… f_4

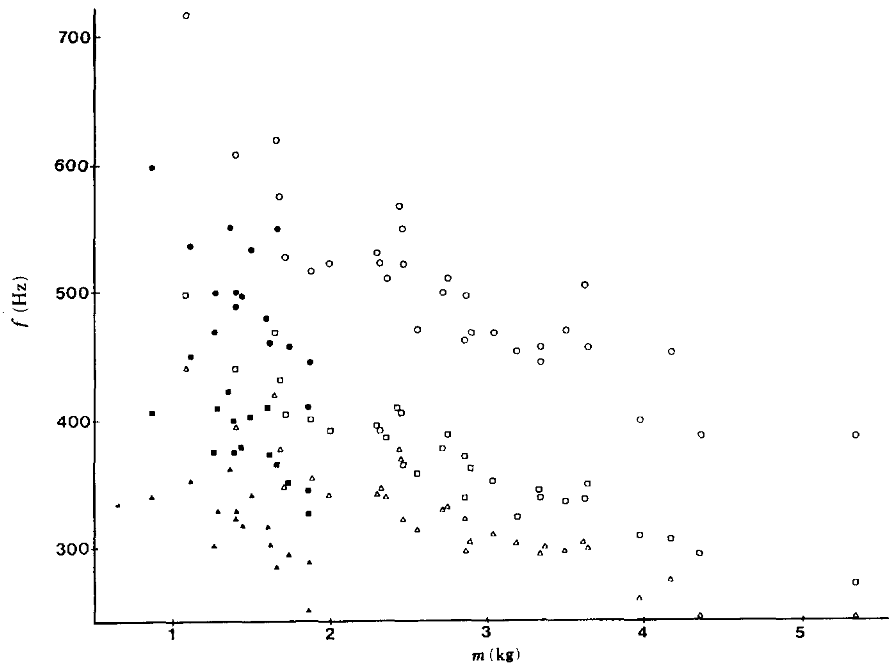

Fig. 4. Relations between f and m for 1982 samples

▲……f_1 (harvested on 10/22) □……f_2 (harvested on 11/8 or 11/17)
△……f_1 (harvested on 11/8 or 11/17) ●……f_3 (harvested on 10/22)
■……f_2 (harvested on 10/22) ○……f_3 (harvested on 11/8 or 11/17)

There were remarkable differences in external appearance between 1982 samples and 1983 samples. Samples tested in 1982 showed normal external appearance (mass and shape) of this cultivar. Samples tested in 1983 had small mass and showed some deviation from spherical shape. In this experiment, on each date of harvest in 1983, Japanese radish roots showing least deviation from spherical shape were chosen as test samples. The cause is considered to be attributed to unseasonable weather, *i.e.* abnormal hotness and dryness in September 1983. The difference of natural frequency within harvest dates are significant for 1983 samples and not significant for 1982 samples. This can be related to a great mass difference of 1983 samples within harvest dates. E' and E'' are in the order of 10^7dyne/cm^2 and 10^6dyne/cm^2 respectively. E'_v and E''_v show values about three times as much as E'_r and E''_r respectively. The frequency dependence of dynamic viscoelastic constants is a probable cause of this discrepancy. In this study, E'_r and E''_r are measured at 2.5Hz, on the other hand, E'_v and E''_v are calculated from the resonance curve in the frequency range of 20-60Hz. The dynamic Young's moduli of apple flesh[2], watermelon flesh[4] and Japanese radish roots measured by the vibrating reed method are in the same order of magnitude (10^7dyne/cm^2). E'_v of Japanese radish roots is about two or three times as much as E'_v of watermelon flesh[2] (from 1.5 to 3.9×10^7dyne/cm^2) and is slightly higher than E'_v of apple flesh[4] (from 3 to 7×10^7dyne/cm^2 for apples stored at 0°C). The differences in the magnitude of E'_v value among these three agricultural products correspond to the difference in sensory flesh firmness of these products. For both 1982 and 1983 samples, there is a tendency that breaking stress and breaking energy for samples harvested on late date are small as compared with samples harvested on early date. This might indicate that texture of Japanese radish root becomes soft with time. However, E' and E'_{app} do not show apparent tendency of this kind. This discrepancy might be attributed to the texture difference between in the region of large deformation and in the region of small deformation. Since breaking

Table 1 . Mean values (upper) and standard deviations (lower) of quality parameters for Japanese radish (Shogoin) roots tested in 1982.

	harvested on 10/22	harvested on 11/8	harvested on 11/17	all samples
m	1465^a	2498^b	3098^b	2353
(g)	275	870	955	1010
ρ	0.949^a	0.941^{ab}	0.938^b	0.943
(g / cm^3)	0.006	0.011	0.011	0.010
f_1	315.7^a	334.3^a	320.9^a	323.5
(Hz)	28.8	46.1	46.6	41.2
f_2	386.0^a	380.6^a	363.6^a	376.5
(Hz)	32.5	50.3	49.3	44.9
f_3	497.3^a	514.6^a	491.7^a	501.2
(Hz)	47.8	77.8	61.5	63.0
$m^{2/3}\rho^{1/3}f_1^2$	12.5^a	19.1^b	20.5^b	17.4
($\times 10^6$gHz^2/cm)	1.7	1.5	2.5	4.0
$m^{2/3}\rho^{1/3}f_2^2$	18.7^a	24.8^b	26.3^b	23.2
($\times 10^6$gHz^2/cm)	2.3	1.9	2.4	4.0
$m^{2/3}\rho^{1/3}f_3^2$	30.9^a	45.1^b	48.4^b	41.5
($\times 10^6$gHz^2/cm)	4.3	4.1	5.6	9.0
E'_v	—	6.45^a	6.51^a	—
($\times 10^7$dyne/cm^2)	—	1.21	1.92	—
E''_v	—	6.07^a	6.28^a	—
($\times 10^6$dyne/cm^2)	—	1.28	2.06	—
E'_r	1.45^a	2.08^b	2.17^b	1.90
($\times 10^7$dyne/cm^2)	0.29	0.27	0.29	0.43
E''_r	1.85^a	2.02^a	1.88^a	1.92
($\times 10^6$dyne/cm^2)	0.29	0.28	0.20	0.27
Breaking stress	8.77^a	7.89^{ab}	7.40^b	8.01
(kgw/cm^2)	1.18	1.08	1.27	1.29
Breaking strain	0.43^a	0.43^a	0.44^a	0.43
	0.03	0.03	0.03	0.03
E'_{app}	25.3^a	26.9^a	26.0^a	26.1
(kgw/cm^2)	2.2	3.9	3.8	3.4
Breaking energy	127^a	119^{ab}	108^b	118
(kgwmm)	.17	19	18	19

Mean values followed by the same letter within harvest dates are not significantly different (1 % level).

Table 2. Mean values (upper) and standard deviations (lower) of quality parameters for Japanese radish (Shogoin) root harvested in 1983.

	harvested on 10/17	harvested on 10/27	harvested on 11/8	harvested on 11/21	harvested on 12/6	all samples
m	173^{a}	422^{b}	732^{c}	1117^{d}	1305^{d}	790
(g)	24	72	113	282	320	444
ρ	0.979^{a}	0.969^{b}	0.971^{b}	0.970^{b}	0.973^{ab}	0.972
(g / cm^3)	0.003	0.005	0.005	0.006	0.007	0.006
f_1	648.0^{a}	646.3^{a}	538.1^{b}	440.8^{c}	468.0^{c}	536.9
(Hz)	43.2	53.0	43.4	43.9	34.4	94.9
f_2	1055.7^{a}	853.7^{b}	699.1^{c}	563.8^{d}	581.8^{d}	725.3
(Hz)	51.1	54.9	44.4	55.7	42.8	180.5
$m^{2/3}\rho^{1/3}f_1^2$	12.9^{a}	23.0^{bcd}	23.1^{b}	20.2^{c}	25.5^{d}	21.2
($\times 10^6$gHz^2/cm)	1.4	2.1	1.8	1.1	1.4	4.2
$m^{2/3}\rho^{1/3}f_2^2$	34.1^{a}	40.1^{b}	38.9^{b}	33.0^{a}	39.3^{b}	37.0
($\times 10^6$gHz^2/cm)	2.0	2.6	2.2	1.9	1.9	3.6
E'_v	3.55^{a}	5.70^{b}	5.46^{b}	4.46^{ab}	5.53^{b}	4.98
($\times 10^7$dyne/cm^2)	1.04	0.96	1.14	0.74	0.90	1.19
E''_v	4.62^{a}	6.42^{b}	5.94^{ab}	5.16^{a}	5.80^{ab}	5.61
($\times 10^6$dyne/cm^2)	1.05	0.68	0.80	0.49	0.50	0.90
E'_r	2.01^{a}	2.75^{b}	2.63^{bc}	2.22^{ac}	2.42^{bc}	2.42
($\times 10^7$dyne/cm^2)	0.24	0.23	0.26	0.43	0.22	0.39
Breaking stress	14.23^{a}	11.41^{b}	10.90^{b}	9.90^{b}	9.88^{b}	11.06
(kgw/cm^2)	0.96	1.61	1.53	0.77	0.94	1.87
Breaking strain	0.41^{a}	0.44^{a}	0.44^{a}	0.44^{a}	0.42^{a}	0.43
	0.02	0.02	0.03	0.02	0.02	0.02
E'_{app}	37.9^{a}	34.0^{a}	37.8^{a}	28.9^{b}	35.0^{a}	34.4
(kgw/cm^2)	2.7	2.5	5.3	2.3	4.0	5.0
Breaking energy	168^{a}	158^{ab}	152^{ab}	143^{ab}	137^{b}	151
(kgwmm)	17	22	18	10	10	18

Mean values followed by the same letter within harvest dates are not significantly different (1 % level).

Table. 3. Correlation coefficients between quality parameters of Japanese radish (Shogoin) roots tested in 1982.

	ρ	f_1	f_2	f_3	$m^{2/3}\rho^{1/3}f_1^2$	$m^{2/3}\rho^{1/3}f_2^2$	$m^{2/3}\rho^{1/3}f_3^2$	E'_r	E''_r	B. stress	B. strain	E'_{app}	B. energy
m	−0.548**	−0.589**	−0.780**	−0.621**	0.454*	0.429*	0.491**	0.397*	0.011	−0.569**	−0.025	−0.313	−0.611**
ρ		0.413*	0.503**	0.459*	−0.155	−0.138	−0.139	0.014	0.289	0.679**	−0.043	0.473*	0.507**
f_1			0.931**	0.929**	0.402*	0.377	0.325	0.346	0.314	0.381*	0.043	0.594**	0.483**
f_2				0.895**	0.109	0.158	0.045	0.094	0.214	0.496**	0.080	0.548**	0.618**
f_3					0.261	0.233	0.319	0.222	0.185	0.368	0.089	0.526**	0.556**
$m^{2/3}\rho^{1/3}f_1^2$						0.957**	0.929**	0.852**	0.345	−0.190	−0.097	0.391*	−0.219
$m^{2/3}\rho^{1/3}f_2^2$							0.879**	0.827**	0.334	−0.146	−0.063	0.418*	−0.161
$m^{2/3}\rho^{1/3}f_3^2$								0.791**	0.242	−0.232	−0.051	0.332	−0.169
E'_r									0.559**	−0.079	−0.037	0.377	−0.102
E''_r										0.279	−0.106	0.338	0.182
Breaking stress											0.018	0.561**	0.782**
Breaking strain												−0.334	0.336
E'_{app}													0.464*

* ·········Significant at 1 % level   **·········Significant at 0.1% level

Table 4. Correlation coefficients between quality parameters of Japanese radish (Shogoin) roots tested in 1983.

	ρ	f_1	f_2	$m^{2/3}\rho^{1/3}f_1^2$	$m^{2/3}\rho^{1/3}f_2^2$	E'_v	E''_v	E'_r	B. stress	B. strain	E'_{app}	B. energy
m	−0.414*	−0.903**	−0.917**	0.485*	−0.088	0.128	−0.008	−0.133	−0.682**	0.192	−0.424*	−0.496*
ρ		0.383	0.459*	−0.234	0.075	−0.013	−0.060	0.010	0.543**	−0.445*	0.573**	0.277
f_1			0.909**	−0.231	0.307	0.053	0.192	0.255	0.683**	−0.202	0.524**	0.554**
f_2				−0.567**	0.102	−0.207	−0.087	−0.029	0.797**	−0.288	0.484*	0.576**
$m^{2/3}\rho^{1/3}f_1^2$					0.662**	0.666**	0.619**	0.569**	−0.465*	0.195	0.076	−0.196
$m^{2/3}\rho^{1/3}f_2^2$						0.605**	0.622**	0.572**	0.104	0.005	0.520**	0.259
E'_v							0.922**	0.602**	−0.184	−0.026	0.282	−0.059
E''_v								0.603**	−0.116	0.052	0.259	0.044
E'_r									−0.063	0.102	0.270	0.048
Breaking stress										−0.176	0.623**	0.839**
Breaking strain											−0.334	0.322
E'_{app}												0.489*

* ·········Significant at 1 % level   **······Significant at 0.1% level

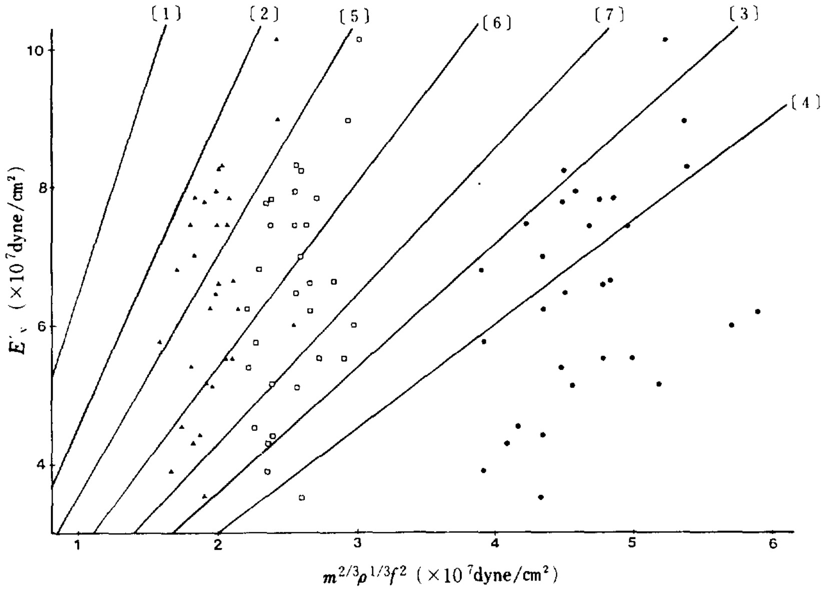

Fig. 5. Relations between E'_V and $m^{2/3}\rho^{1/3}f^2$ for 1982 samples

▲ …… $m^{2/3}\rho^{1/3}f_1^2$
□ …… $m^{2/3}\rho^{1/3}f_2^2$
● …… $m^{2/3}\rho^{1/3}f_3^2$

[1] : $E'=6.414m^{2/3}\rho^{1/3}f^2$ (${}_0S_2$, $\nu=0$) [2] : $E'=4.521m^{2/3}\rho^{1/3}f^2$ (${}_0S_2$, $\nu=0.5$)
[3] : $E'=1.794m^{2/3}\rho^{1/3}f^2$ (${}_1S_2$, $\nu=0$) [4] : $E'=1.522m^{2/3}\rho^{1/3}f^2$ (${}_1S_2$, $\nu=0.5$)
[5] : $E'=3.506m^{2/3}\rho^{1/3}f^2$ (${}_0S_0$, $\nu=0$) [6] : $E'=2.698m^{2/3}\rho^{1/3}f^2$ (${}_0S_3$, $\nu=0.4$)
[7] : $E'=2.145m^{2/3}\rho^{1/3}f^2$ (${}_0S_3$, $\nu=0$)

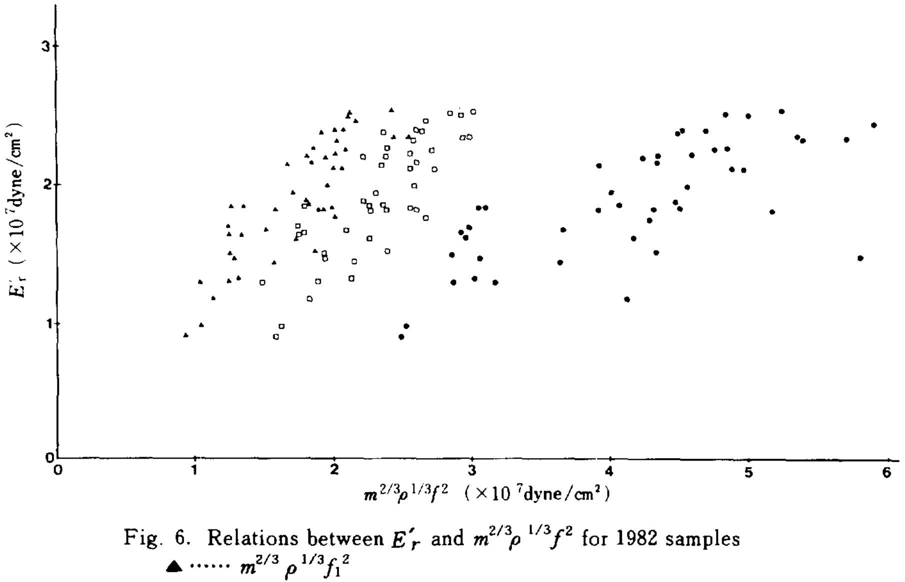

Fig. 6. Relations between E'_r and $m^{2/3}\rho^{1/3}f^2$ for 1982 samples

▲ …… $m^{2/3}\rho^{1/3}f_1^2$
□ …… $m^{2/3}\rho^{1/3}f_2^2$
● …… $m^{2/3}\rho^{1/3}f_3^2$

stress and breaking energy are measured at large deformation, on the other hand, E' and E'_{app} are measured at small deformation.

The correlation coefficients between quality parameters of samples tested in 1982 and 1983 are summarized in Table 3 and 4 respectively. There are significant correlation coefficients between $E'$and nondestructive indices $m^{2/3}\rho^{1/3}f_i^2$ (i=1, 2, 3 for 1982 samples, i=1 ,2 for 1983 samples). The relations between the dynamic Young's modulus and the nondestructive index $m^{2/3}\rho^{1/3}f^2$ for samples tested in 1982 are shown in Fig.5 and 6. Using a homogeneous elastic sphere model, the theoretical relations between E' and the natural frequencies of spherical fruit were deduced(3) and applied to apples(3) and watermelons(4) in previous papers. In this paper, these relations are applied to spherical Japanese radish roots. Fig.5. also shows the straight lines which represent the theoretical relations between E' and $m^{2/3}\rho^{1/3}f^2$ for several low frequency modes of spheroidal class. The experimental results of E'_v *vs.* $m^{2/3}\rho^{1/3}f^2$ coincide with the theoretical relations derived from a homogeneous elastic sphere model within an order of magnitude although the corresponding modes for the natural frequencies f_1 , f_2 and f_3 are not clearly identified. This suggests the validity of the acoustic impulse response method for estimating the internal textural quality of spherical Japanese radish roots.

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聖護院ダイコンの動的粘弾性及び音響特性

山本博道・萩沼之孝

聖護院ダイコンの動的粘弾性定数を強制振動による方法で測定し，固有振動数を打音より測定した。動的ヤング率は，固有振動数を含む非破壊の指標と，有意の相関関係にあった。