Mechanical resonance method for evaluation of peach fruit firmness

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ABSTRACT: An investigation was carried out to establish the basic relationship between mechanical resonance, firmness, chemical composition and ethylene production during the maturity time and the ripening time of peach fruit. The stiffness factor calculated by a non-destructive frequency response technique was compared with biological properties obtained by measurement of chemical composition, firmness and ethylene production in the internal atmosphere of tested fruit. The correlation between the biological multifunction and the mechanical resonance frequency of peach fruit can be expressed by an exponential relationship. Multifactorial index seems to describe the rupture point that for peach fruit coincides with the beginning of climacteric developmental stage, detected by ethylene production.

Keywords: peach fruit; *Prunus persica* Borh.; firmness; mechanical resonance; stiffness factor; ethylene; indices of ripening

Ripening is a term used to encompass many processes that may occur simultaneously or sequentially and may be independent or associated together. Supplemental ethylene may be affected by many of these processes. Autocatalysis of ethylene production is a characteristic feature of ripening fruits and other senescing tissues in which the massive increase in ethylene production is triggered by the exposure of ethylene. The amount of endogenous ethylene, produced by a tissue, generally increases autocatalytically at the specific stage of growth or development to initiate a physiological response. At concentrations as low as 0.1 µl/l ethylene can induce a wide array of physiological responses, including texture expressed as firmness, color, chemical composition and as a maturity index (Watada 1986; Chu 1984). Analyses of the internal concentrations of ethylene are valuable research procedures because they provide measures of the actual physiological activity. Internal gas concentrations are the results of both the rate of production and the rate of the gas diffusion. However, measurements of the internal gas concentrations can give a reasonable estimate of actual physiological activity of the gas within the tissue (Salveit 1982).

Applications of the resonance frequency measurements of biological material are reported for determination of plant tissue rigidity and estimation of turgor pressure (Abbot et al. 1968; Abbot, Lu 1996; Finney, Norris 1968).

An electromagnetic exciter and acceleration measurements are used to obtain the frequency response and the resonance frequency of tested fruit. The square of the frequency of this resonance multiplied by the mass of the fruit, designated by f^2m, was termed the stiffness coefficient of the fruit (Mohsenin 1966). The measurement of $f^2m^{2/3}$ parameter of the fruit can be used as an evaluation parameter.

MATERIAL AND METHODS

Measurement of mechanical resonance

It is necessary to know the resonance frequency to obtain the relationship between stiffness factor (firmness of the peach fruit) and the maturity time and ripening time (Yamamoto et al. 1980). The stiffness factor S is calculated by (1) (Chen 1993; De Baerdermaeker et al. 1982).

$$S = f^2 m^{2/3} \qquad (1)$$

where: f – resonant frequency of tested peach fruit (Hz),
m – mass of tested peach fruit (g).

An electromagnetic exciter (shaker) and acceleration measurements are used to obtain frequency response and resonant frequency. The measurement diagram is shown in Fig. 1.

Tested fruit is placed on the shaker that is driven through the power amplifier from the signal generator in PULSE multianalyzer. To protect the fruit the foam rubber is placed between the shaker and the fruit. The electrical current meter (Ammeter) is used to provide the constant excitation for each tested peach fruit. Two accelerometers (Brüel & Kjaer, Model 4507 B 001 with sensitivity 9.89 mV/g and Model 4507 B 004 with sensitivity 95.2 mV/g) are used to measure frequency responses. The former, shaker accelerometer measures

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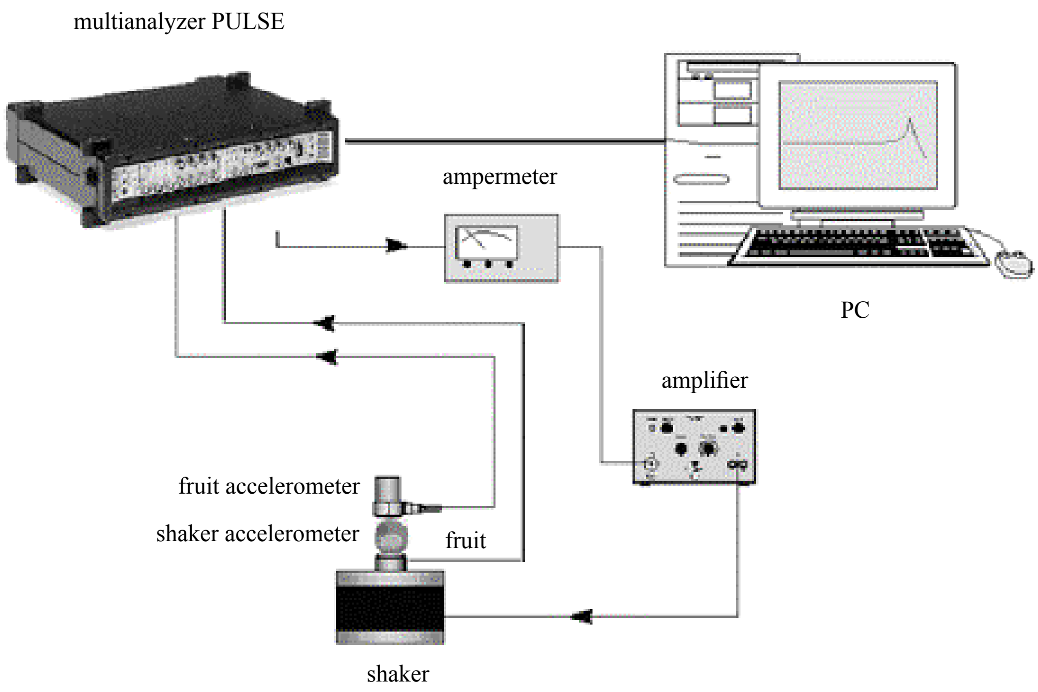

Fig. 1. Concept of mechanical resonance measurement. Non-destructive resonance tests were constructed on the whole intact fruit using an electromagnetic vibrator (instruments identified in the text). Typical peaks were recorded as illustrated in Fig. 2

the acceleration of the shaker only and the latter, fruit accelerometer measures the acceleration of the fruit and the shaker together. Signals from the accelerometer are processed by the Brüel & Kjaer multianalyzer PULSE. The frequency response $H(\omega)$ of tested peach fruit is calculated by (2).

$$H(\omega) = Hf(\omega)/Hs(\omega) \quad (2)$$

where: $Hf(\omega)$ – frequency response measured with fruit accelerometer (m/s^2),

$Hs(\omega)$ – frequency response measured with shaker accelerometer (m/s^2),

ω – angular frequency $\omega = 2\pi f$ (rad/s),

f – frequency (Hz).

The harmonic signal from PULSE signal generator is swept over the frequency range 50 Hz – 1.6 kHz. Fig. 2 presents a typical frequency response of tested peach. The highest peak from the spectrum was used for further processing and calculation of stiffness factor S using (1).

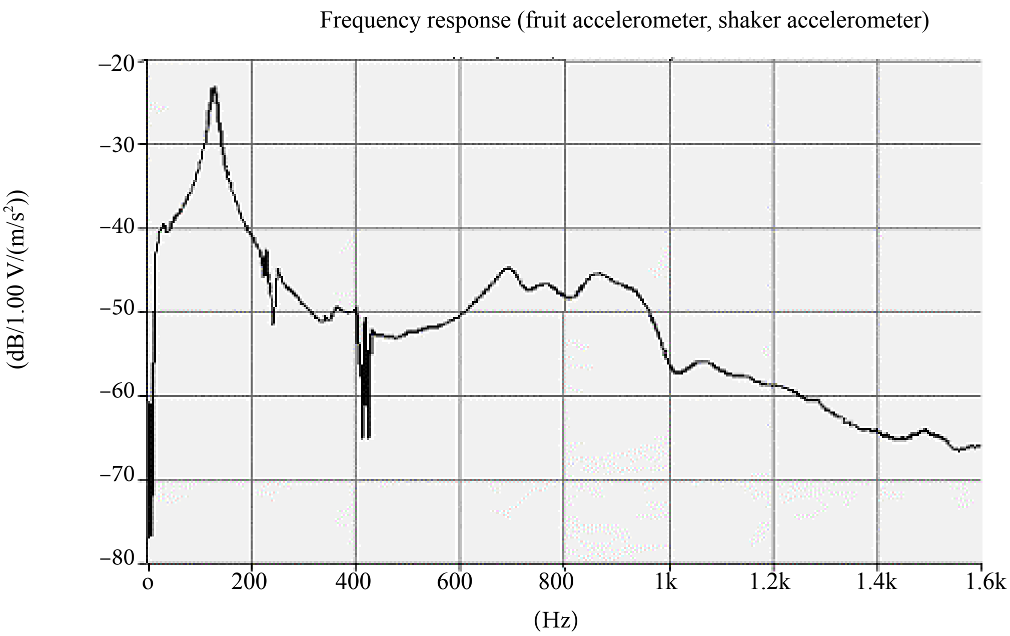

Fig. 2. Frequency response curves for 150g peach fruit. First peaks to 200 Hz were tested in Figs. 3 and 4

The mass of each tested peach fruit was measured with precision balance.

Sampling of peach fruits

South Haven peach fruits grown in an orchard of the research center were used for measurements. Peaches were harvested in the afternoon, transferred to the room temperature and all the parameters were measured next day. Harvesting intervals started from mid-June with the constant interval of one week during five weeks. 12 peach fruits were measured on each of these five measurement days.

At the end of the measurements the ripest peach fruits from the last period were stored at a room temperature, numbered from 1 to 12 and their mechanical properties were measured every day from early ripe stage to late ripe stage (4 days).

Measurement of texture properties

The peach texture was measured as a penetration test with cylindrical plunger of 8 mm diameter and constant speed 10 mm/min, 8 mm deep into tissue. Force deformation curves from penetration tests were plotted to express the skin resistance of tested peach fruits. The firmness of the tissue of tested peach is obtained from the rupture point. Each fruit was penetrated at the opposed locations to obtain skin deformation curve. The compression force expressed as the firmness for skin and flesh of tested peach was sampled and saved in the hard disk of the computer. The mean of four measurements was used to represent the firmness of each tested peach.

Measurement of ethylene in atmosphere of impacted fruit

A partial vacuum was applied to the tissue submerged in an aquatic solution. Gas bubbles leave out the fruit, rise in the solution and accumulate at the top of the submerged container. A sample (1 ml) of extracted gas was injected in the stainless steel column (1.2 m × 3 mm) packed with Porapak Q (60–80 mesh). Ethylene concentration was determined using an external standard of 110.7 µl/l ethylene calibration gas certified by Linde Products, Czech Republic.

Measurement of chemical composition

Twelve fruits were individually weighed and analyzed for titratable acidity (expressed as percentage of malic acid) measured with 0.1 NaOH up to pH 8.1; soluble solids were given as degrees of refractometric value with Abbé refractometer (Jena Werk, Germany).

Statistical analysis

Twelve replications were provided for each measurement described above, means and standard errors are presented in figures. In addition, four puncture tests were made for each peach fruit during measurements of texture properties.

RESULTS AND DISCUSSION

Mechanical resonance technique for measurement of stage of ripening

From the measurements of frequency response of tested fruits it is possible to see a resonance frequency shift during the ripening time of peach fruit. This shift of resonance frequency is caused by the softening of the peach fruit tissue. A decrease in the resonance frequency during 14 days is 31 Hz (from 148 to 117 Hz). Stiffness factor calculated using (1) increases by about $3.4e^4$ $Hz^2g^{2/3}$ during the same period. The increase in stiffness factor is caused by the increasing mass of peach fruits during the ripening time. Figs. 3 and 4 show the stiffness factor and resonance frequency as functions of ripening time.

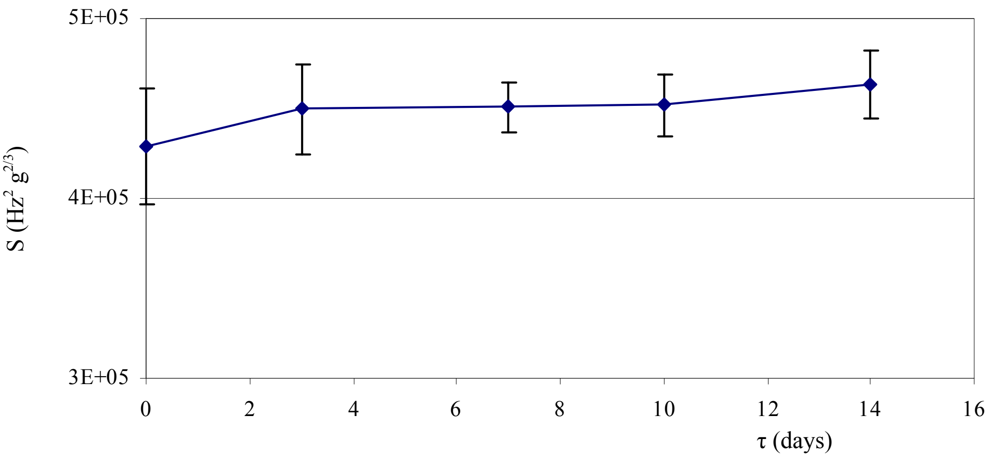

Fig. 3. Stiffness factor of peach fruit by equation (2) during the ripening time. Each point is the mean of 12 replications. Vertical bars indicate standard errors

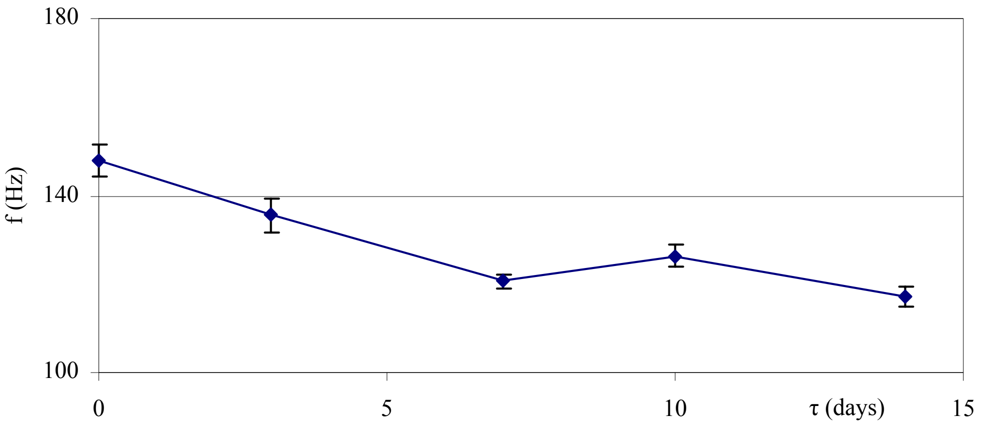

Fig. 4. Resonance frequency of peach fruit during the ripening time. Each point is the mean of 12 replications. Vertical bars indicate standard errors

Evaluation of peach fruit softening in the ripening phase

Softening of the fruit, caused by spontaneous pectolysis of pectocelluloses and protopectin, is frequently evaluated by penetrometric firmness of skin and flesh. Peach fruit texture during ripening was expressed by deformation curves and estimation of basic parameters of firmness. To study the ripening of fruits, measurements of loading compression with skin in-intact of flesh of the peach fruit were made. The results are presented in Fig. 5.

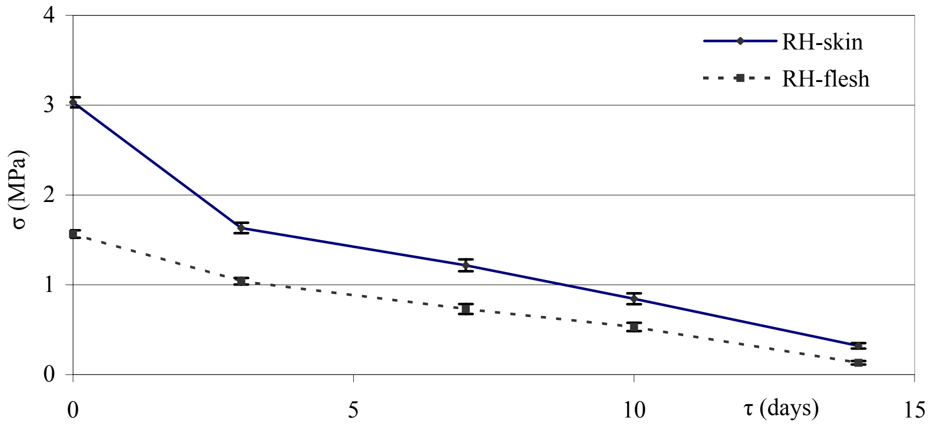

Fig. 5. Firmness of tissue and flesh of peach fruit during the ripening time. Each point is the mean of 12 replications. Vertical bars indicate standard errors

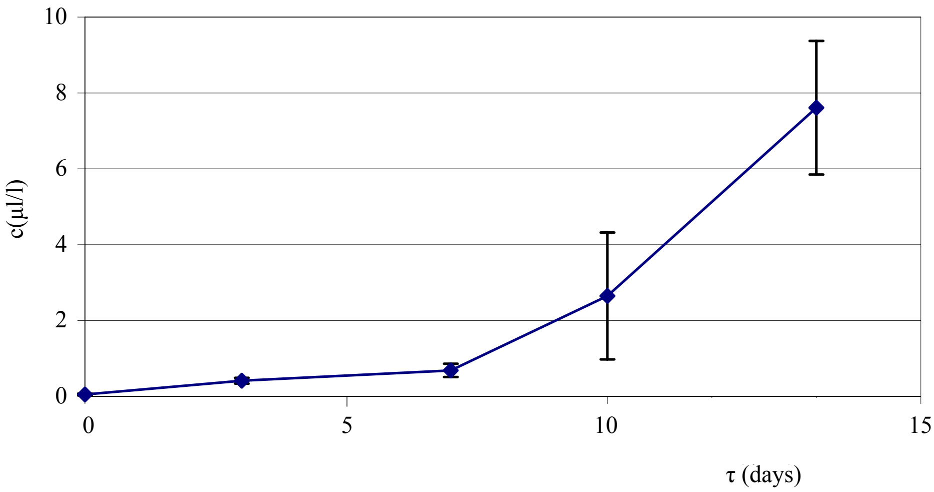

Fig. 6. Concentration of ethylene in peach fruit. Each point is the mean of 12 replications. Vertical bars indicate standard errors

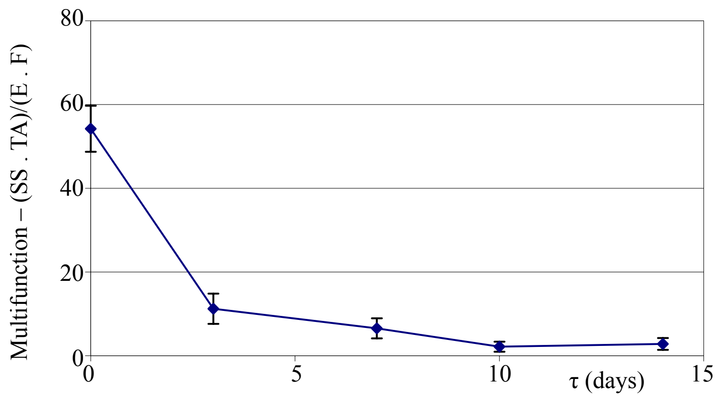

Fig. 7. Biological multifunction of peach fruit during the ripening time. Each point is the mean of 12 replications for parameters (SS × TA/Ethylene × Firmness). Vertical bars indicate standard errors

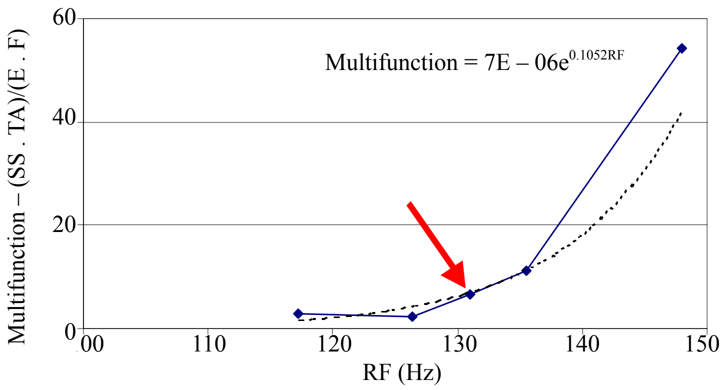

Fig. 8. Relationship between peach fruit biological multifunction and stiffness (dashed line – regression curve). Each point was constructed from parameters (SS × TA/Ethylene × Firmness) and stiffness factor from equation (2)

Ethylene production in the ripening stages

The climacteric phase is studied by measuring ethylene in the internal atmosphere of fruit. Recent studies have indicated that ethylene promotes the ripening and senescence of peach fruit in orchard conditions. In the physiological age study, the internal ethylene concentration in peach fruit remained below 0.1 µl/l until July 10 (Fig. 6). There was a significant increase to 3 µl/l on July 20. From this date the climacteric stage started and the endogenous ethylene increased to more than10 µl/l.

Chemical properties of peach fruit during ripening

From the physiological point of view maturation is a continuum of many parallel processes of biosynthesis and hydrolysis of supply substances. According STREIF (1989) criteria of ripening are based on objective measurements of parameters significantly influencing the physical and chemical properties of fruit. Soluble solids (refractometer readings) were slightly affected by picking date at the last values. Differences in the harvesting time were slightly reflected in climacteric phase maturity while the onset of climacteric phase was indicated by ethylene evaluation. Titratable acidity decreased for unripe and ripe fruits.

Multi-factorial indices are based on the hypothesis of their expected exponential (or linear) trends with further stabilization of values and that they would differentiate the ripening process more easily. Moreover, each factor (tissue composition, physical parameter) is expected to be measured by objective and expeditious methods. Fig. 7 shows biological multifunction defined

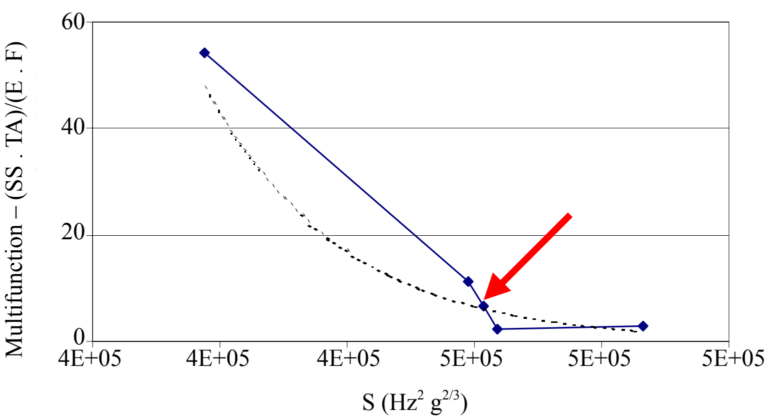

Fig. 9. Relationship between peach fruit biological multifunction and resonant frequency (dashed line – regression curve). Each point was constructed from parameters (SS × TA/Ethylene × Firmness) vs. resonant frequency

as a multiplication of titratable acidity and soluble solids divided by firmness and ethylene production of peach fruit.

Relationship between firmness and stiffness of peach fruit

Further combinations of ripening criteria (constructed in four-factorial index) are shown in Figs. 8 and 9. Relations between the stiffness factor, mechanical resonance and biological multifunction of peach fruits are presented as non-linear functions of stiffness and constructed multifactorial index. Red arrows show the maturity time of peach fruits and dashed lines represent regression exponential curves. The inflection point of multifactorial indices coincides with the beginning of a climacteric increase in ethylene production.

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Mechanická rezonance plodů pro hodnocení pevnosti broskví

ABSTRAKT: Článek se zabývá nalezením vztahů mezi mechanickou rezonancí broskví, tuhostí jejich dužniny a slupky, jejich chemickým složením a produkcí etylenu během zrání. Činitel tuhosti (stiffness factor), určený na základě nedestruktivního měření frekvenční charakteristiky, byl porovnáván s biologickými vlastnostmi plodů získanými měřením chemického složení, tuhosti a množství etylenu ve vnitřní atmosféře zkoumaného plodu. Výsledkem korelací mezi biologickou multifunkcí a mechanickou rezonancí, získaných těmito měřeními, je exponenciální charakteristika. Multifunkční index ukazuje bod zvratu, který se shoduje se začátkem klimakterické vývojové fáze, detekované pro etylen.

Klíčová slova: broskve; *Prunus persica* Borh.; pevnost; rezonance; činitel tuhosti; etylen; údaje o zrání

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