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Acoustic vibration method for food texture evaluation using an accelerometer sensor

Shin-ichiro Iwatani [a], Hidemi Akimoto [b], Naoki Sakurai [a,*]

[a] Graduate School of Biosphere Sciences, Hiroshima University, Higashi-Hiroshima 739-8521, Japan
[b] Collaborative Research Center, Hiroshima University, VBL Office, 2-313, Kagamiyama, Higashi-Hiroshima 739-8527, Japan

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ABSTRACT

A piezoelectric element has been used in an acoustic vibration method for measuring food texture. While it is inserted into a food sample, the piezoelectric element detects the vibration of a probe. The frequency response of the piezoelectric sensor used for the acoustic vibration method was evaluated with a laser Doppler vibrometer (LDV). The output voltage from the piezoelectric sensor, which was driven to vibrate at 23 different frequencies, was monitored and compared with the velocity signal obtained by the LDV. The output signal was substantially affected by the vibration frequencies. The output signals corresponded to displacement of the probe below 3 Hz, to velocity from 10 to 70 Hz, and to the acceleration force from 680 to 1500 Hz. These results clearly indicate that a piezoelectric sensor is impractical to use for the texture measurement and should be replaced with an accelerometer that always generates an acceleration signal irrespective of the applied vibration frequencies. The results also demonstrated that the previously defined texture index (TI) was misleading and overestimated the texture of food at probe vibration frequencies above 10 Hz. Our replacement of the sensor led us to define a new energy texture index (ETI). ETI measurement of several foods, including biscuit, Japanese cracker and vegetables were presented and the effects of water activity of cracker on the index were examined.

1. Introduction

There have been many studies using acoustic measurements for food evaluation (Arimi et al., 2010; Chen et al., 2005; Duizer and Campanella, 1998; Maruyama et al., 2008; Roudaut et al., 1998; Sanz et al., 2007). The principle common to these studies is the assumption that one evaluates food texture by the sound generated while food is masticated in the mouth. Therefore, most of these studies used a microphone to detect the sound of the sample breaking (see Duizer, 2001; Taniwaki and Sakurai, 2010a for review). The microphone method for recording mastication sounds from the panelists has several drawbacks for quantitative and reproducible evaluation of food texture, such as variations in the microphone performance (Chen et al., 2005), the experimental conditions (room size, arrangement of auditory equipment, and environmental noise), the resonant frequencies of the mouth cavity and the skull bone connected to the mouth (van der Bilt et al., 2010), and the quantity and rate of saliva during mastication (Szczesniak, 2002). Most of the above drawbacks stem from the inevitable variation between the individual panelists. To avoid these drawbacks related to microphone recording, an acoustic emission sensor has recently been introduced to obtain pulse sound signals on food breakage (Makino et al., 2002; Marzec et al., 2007; Zdunek et al., 2010).

An acoustic vibration method for food texture has been developed (Sakurai et al., 2005). Food texture is quantitatively evaluated in terms of the texture index (TI) which is defined as an energy density (Taniwaki and Sakurai, 2008). This method uses a probe mimicking a human incisor or canine tooth. The probe is inserted into the food sample, and the vibration of the probe that occurs while breaking the sample is detected by a piezoelectric sensor that is directly attached to the probe. Sound from the panelist's mouth is essentially derived from information including the vibrations of food and teeth during mastication. Therefore, an acoustic vibration method that directly detects the vibrations of the probe while the probe breaks the food has the advantage that it detects more information about food texture than the microphone method described above.

The acoustic device mentioned above uses a piezoelectric element as a sensor to detect probe vibration. The piezoelectric element used is made of $Pb(Zr,Ti)O_3$ (PZT) and is of the ceramic discoidal type. This type of piezoelectric sensor is usually used in

Abbreviations: LDV, laser Doppler vibrometer.

* Corresponding author. Address: Graduate School of Biosphere Sciences, Hiroshima University, Kagamiyama 1-7-1, Higashi-Hiroshima 739-8521, Japan. Tel./fax: +81 82 424 6516.

E-mail address: nsakura@hiroshima-u.ac.jp (N. Sakurai).

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the range from several kHz to several MHz, and rarely used in the range below 20 kHz. The TI was defined below the upper limit of the human auditory range, about 20 kHz, and based on the assumption that the output voltage from the piezoelectric sensor corresponds to the displacement of the sensor (Taniwaki and Sakurai, 2008). They reported the relation between the output voltage of the sensor, V, and the static load, P, as P (Pa) = $1.1 \times 10^7 V + 1.0 \times 10^6$. This relation was statically obtained. As far as we know, no one has measured the frequency response of piezoelectric elements to vibrations below 20 kHz. Acoustic evaluation of food texture is carried out in the audible range from several Hz to 20 kHz. Therefore, the properties of the element below 20 kHz should be examined.

Precise examination of the frequency response of the piezoelectric element disclosed that the output voltage of the element is governed by very complex physical properties, leading us to propose an alteration of the sensor and a re-definition of the TI.

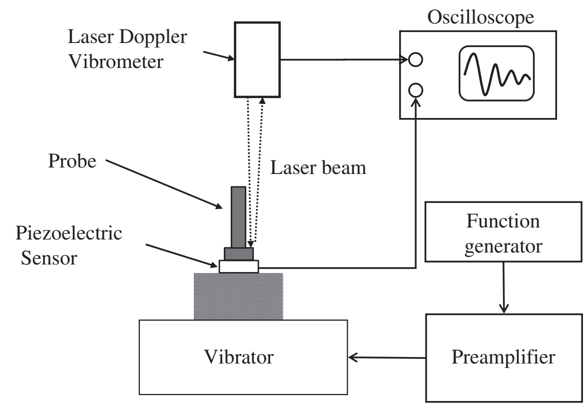

Fig. 2. Experimental setup for comparing output signals from the piezoelectric sensor and the LDV. The vibration of the probe was monitored by LDV. The signals from the LDV and the sensor were introduced into an oscilloscope and the two waveforms were compared to obtain the phase shift.

2. Materials and methods

The probe sensor unit (Fig. 1) consists of a supporting aluminum column (25 mm in diameter and 15 mm long), a stainless-steel wedge-type probe (5 mm in diameter and 20 mm long), and a discoidal piezoelectric sensor (10 mm diameter and 2 mm thick, 2Z10D-SYX, Fuji Ceramics Co., Ltd., Fujinomiya, Japan) sandwiched between the column and probe with an adhesive (Aron Alpha Extra, Toa Gousei Co., Ltd., Tokyo, Japan).

This unit was affixed to the surface of a vibrator (513-B, Emic Co., Ltd., Tokyo, Japan) with a small amount of wax (Fig. 2); the vibrator causes the object to vibrate with a known frequency, which is controlled by PC software (Spectra Plus, Pioneer Hill Software LLC., USA). The vibrator generated 23 different sinusoidal wave signals with frequencies ranging from 3 to 15 kHz. The frequencies used were, 3, 5, 7, 10, 40, 50, 60, 70, 80, 120, 170, 240, 360, 450, 550, 680, 1300, 1920, 3000, 4000, 5000, 7000, and 15000 Hz. The generated signal was amplified by an amplifier (371-A, Emic Co., Ltd., Tokyo, Japan) and sent to the vibrator.

The vibration of the probe was monitored by a laser Doppler vibrometer (LDV, model LV-1720, Ono Sokki Co., Ltd., Yokohama, Japan). The output voltage (V) from the LDV was proportional to the velocity (v) of vibration as follows; v (m/s) = $0.05 \times V$ (volt). The output voltage signals from the LDV and the piezoelectric sensor attached to the probe were connected to an oscilloscope (model VC-6523, Hitachi Kokusai Electric Inc., Tokyo, Japan) to compare the phase difference between the LDV and the sensor output.

In some experiments, we replaced the piezoelectric sensor with an accelerometer. The accelerometer (NP-2710, Ono Sokki Co., Ltd., Yokohama, Japan) was sandwiched between the aluminum column and the probe with adhesive, as described above. The output signal from the sensor was amplified by an amplifier (PS-1300, Ono Sokki Co., Ltd.) and connected to an oscilloscope as described above.

Potato chips (Calbee Inc., Tokyo Japan) were used to compare the texture measurements with the two different types of sensors. These food samples were approximately oval in cross-section with dimensions of roughly 70×50 mm. They were about 1 mm thick, with a curving surface. A number of potato chips ($n = 20$) of a similar size were used for the experiment. Ten of the twenty chips were used for the measurement with a piezoelectric element as the sensor, similar to what was done in a previously reported experiment (Taniwaki and Sakurai, 2010b), and the remaining ten were used with an accelerometer as the sensor. A wedge-type probe was used. The tip angle of the probe was 30°. The vibration signal was divided into nineteen frequency bands, and nineteen corresponding texture indices were calculated, using the same procedure used in previous papers (Taniwaki et al., 2006a; Taniwaki and Sakurai, 2008).

Biscuit (Marie, Morinaga & Co., Ltd., Tokyo), Japanese cracker (Soft Salad, Kameda Seika Co., Ltd., Niigata, Japan), cracker (Premium cracker, Yamazaki-Nabisco Co., Ltd., Tokyo), and agricultural products (radish, lettuce, cucumber and apple) were purchased in the local market. Cracker was trimmed to 20×50 mm piece and used for the study on the effect of water activity of cracker on the texture index. These pieces were placed on a stainless mesh hanging over the solurion in a plastic box ($300 \times 200 \times 110$ mm).

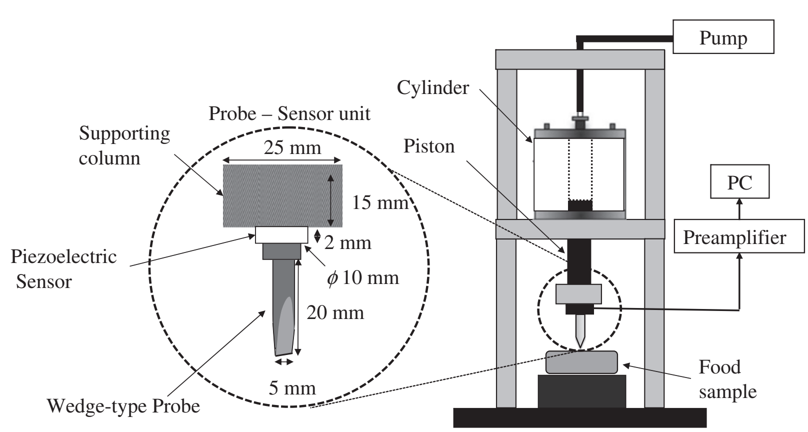

Fig. 1. Device for measurement of the food texture and magnification of the probe sensor unit. The probe-sensor unit is driven by the piston into the food sample. The supporting column was made of aluminum. The wedge-type probe was made of stainless steel.