Device for acoustic measurement of food texture using a piezoelectric sensor

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Abstract

We have developed a device that enables direct measurement of food texture. The device inserts a probe into a food sample and detects the vibration caused by the sample's fracture. A piezoelectric sensor was used to detect that vibration. The frequency response of the piezoelectric sensor was measured. Results showed that the sensor covered the full audio frequency range up to 20 kHz. The device probe was designed so that its resonance was not in the signal detection band. An octave multi-filter was used to analyze the obtained signals. Preliminary data were obtained and used to quantify the sample texture. Quantification of food texture was possible by using the device together with the analytical tool. We also discuss the application of the device to investigation of physical and structural aspects of food.

Key words: acoustic measurement; food texture; piezoelectric sensor

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1. Introduction

Food texture, such as crispness, is an important attribute of fresh produce (fruits and vegetables) when consumers assess their quality. However, texture is subjective and depends on the kind of commodity. An effective solution to this problem is to measure quantitative properties of such food texture and provide an objective standard for it. As one step toward the development of a solution, we developed a device that allows us to measure food's textures directly. The device measures the vibration caused by the fracture of the sample when inserting a probe into the sample. Humans are also inferred to sense such vibration and to evaluate the food texture. We used a piezoelectric sensor because piezoelectric sensors have good sensitivity to small signals and excellent responses over a wide frequency range. In addition, we have developed a new probe for the device. The probe is an important component of the device because it directly contacts with a sample to be examined. We carefully designed the probe by giving attention to its resonance frequency because that resonance markedly distorts the signals.

Extensive studies have addressed food texture. A general method of measuring food texture is to study the sounds produced by food mastication. Drake (1963, 1965) was an early researcher to study foods using the method. Then Vickers and Bourne (1976) set a hypothesis that the crispness sensation was produced by sounds. They proposed a model of the cellular structure to explain the generation of crisp sounds. As a crisp cellular material is crushed, a series of sounds is produced. Each sound results from the fracture of a cell or cell wall. However, Christensen and Vickers (1981) proposed that the vibrations produced by fracturing crisp foods might underlie the perception of crispness because a judgment could be made in the absence of auditory cues. Vickers (1981) later concluded that information reaching the brain by either the auditory or the oral route produced very similar crispness judgments. General discussions of acoustical methods for food texture studies have been reviewed by Duizer (2001), and Roudaut, Dacremont, Pamies, Colas and Le Meste (2002). Most previous studies, including those described above, recorded sounds produced by food mastication (Edmister & Vickers, 1985; Kapur, 1971; Dacremont, Colas & Sauvageot, 1991; Lee, Deibel, Glembin & Munday, 1988; Seymour & Hamann, 1988). One inherent problem of this method is that the intrinsic texture information can be lost because of resonance of the palate or mandible. Furthermore, soft tissues in the mouth absorb or dampen higher frequency sounds (Vickers, 1991). Our device obtained complete signals without such loss because of the factors stated above. The concept of direct measurement of crispness resembles the approach by Vincent (1998, 2004), which was to translate "crispness" into a form that is describable by materials science, and to measure independent parameters at the material and structural levels.

This paper reports the conceptual design of the new device for measuring food texture and characteristics. We show a tool for analyzing the obtained data with the device. Preliminary results obtained through the use of this device are included. Finally, possible improvements to the device and its application to an investigation for further understanding of food texture were discussed from the aspect of mechanical fracture.

2. The device and system

Human beings mainly use three organs to evaluate food texture: the teeth, the nerves and the brain. We masticate food using teeth, detect the texture using nerves and process the signals and perceive the texture of food using the brain. Therefore, a device for measuring food texture should be equipped with these three parts. We developed a device that satisfies these three aspects (Fig. 1). The device was based on the experimental setup reported previously by Sakurai, Iwatani, Terasaki and Yamamoto (2005a, b). In Fig. 1, the probe represents the teeth, the piezoelectric sensor the nerves, and the computer the brain. The probe was inserted into a food sample and the sensor detected the vibrations produced by the fracture of the sample.

The probe we used was a stainless steel screw with a conical tip. The probe was 30 mm long, with 5 mm diameter. The probe's tip angle was 30°. The piezoelectric sensor was a 3-mm-thick discoidal-type unit with 10 mm diameter (Fuji Ceramics Corp., Fuji, Japan). In addition, a 0.4-mm-thick piezoelectric film of 20 mm diameter was tested. This type is widely used for sounding buzzers. The discoidal piezoelectric sensor was bonded directly to a 14-mm-diameter aluminum piston with epoxy adhesive. Figure 1 shows that the piston was housed in a brass cylinder. The 80-mm-diameter cylinder was made of brass with 14 mm i.d. A conveying pump (Hiranuma Sangyo Co. Ltd., Mito, Japan), which contained low-viscosity silicone oil, drove the probe. The vibration signals obtained with the piezoelectric sensor were put into a low-noise preamplifier (SR-560, Stanford Research Systems, Inc., Sunnyvale, CA, USA) and acquired with a computer program developed using LabVIEW (National Instruments Corp. Ltd., Austin, TX, USA) where the data sampling rate was 80 kHz. Data were then analyzed in the frequency domain. We developed an octave multi-filter to perform this analysis using the LabVIEW program, as shown in Fig. 2. Frequency bands of the multi-filter were determined using an octave scale taking into account human auditory sensation. The multi-filter covered up to 25.6 kHz (full audio frequency range).

Using filtered data, we were able to quantify food texture using an algorithm developed previously by Taniwaki, Hanada and Sakurai (2006). The “texture index” value was determined according to the amplitude density of the obtained signals, as

$$\frac{\sum |V_i|}{T}, \tag{1}$$

where $|V_i|$ is the absolute amplitude of each data point in volts and T is the data length in seconds.

3. Characterization of the Device and Results

The brass cylinder with low-viscosity silicone oil allowed smooth movement of the aluminum piston when the probe was driven. This feature minimized the noise caused by the piston movement. The probe speed was 22 mm s^{-1}, which was within a range of actual mastication speed (Roudaut et al., 2002). The probe was able to move over a distance of 30 mm, which was sufficiently long to accommodate insertion of the probe into the food sample.

Frequency responses of the piezoelectric sensors were measured as shown in Fig. 3. Measurement was performed by exciting the piezoelectric sensors with swept sine signals and by measuring their surface vibration using a laser Doppler vibrometer (LDV). The LDV measured the surface motion velocity. We converted the velocity data to displacement data. Figure 3(a) shows the frequency response of the discoidal 3-mm-thick, 10-mm-diameter piezoelectric sensor. We obtained an almost constant frequency response over the full audio frequency range except for 1 kHz or lower. However, fluctuations were observed below 1 kHz.

Figure 3(b) was taken with the piezoelectric film of 0.4 mm thick and 20 mm in diameter. Using an acrylic holder with a slight gap that allowed the piezoelectric film to vibrate effectively, the piezoelectric film was sandwiched for testing this type. Larger displacement was obtained for the same input signals because this type was much thinner than the discoidal type. An almost constant frequency response was obtained up to about 6 kHz and in the low-frequency region down to about 20 Hz.

Resonances of the probe should be higher than 20 kHz because our frequency of interest was the full audio frequency range (up to 20 kHz). We designed the probe so that the lowest resonance frequency was much higher than the observation frequency range, as described in Fig. 4. We estimated the lowest resonance frequency of the probe of various diameters by assuming, for convenience, that the probe was cylindrical, but it was actually conical at the tip (Fig. 5). The following standard formula for the lateral mode was used to estimate the lowest resonance of the probes (Rao, 1990).

$$\omega = (\beta l)^2 \sqrt{\frac{EI}{\rho A l^4}} \tag{2}$$

In that equation, ω represents the angular frequency, E is the Young's modulus, I is the area moment of inertia, ρ is the density, A is the cross sectional area, and l is the length. The factor βl was 1.875 for the fixed-free boundary condition (Rao, 1990). We used parameters $\rho = 7.9 \times 10^3$ kg m^{-3} and $E = 2.0 \times 10^{11}$ Pa for steel. For the 5-mm-thick and 30-mm-long probe, the estimated resonance was calculated as 25 kHz. The longitudinal mode frequency was higher than the lateral mode frequency. Although the actual resonance should be lower than that of the estimation for cylindrical shape, that estimation is useful if it is well above the frequency range of interest. Furthermore, the brass cylinder was designed to be massive and sufficiently thick to avoid interfering resonances that would otherwise distort the acquired signals.

Figure 6 shows typical signals obtained using the device for an apple sample. Typical signals can be characterized by near-random variation of the amplitudes in the time domain. The signals were in a short period of time about 0.6 s when the probe moved some 10 mm into the sample. Figure 7 (a) shows the calculated texture indices (determined by Eq. 1) for apples, persimmons and pears using filtered texture signal data. The texture indices were calculated for each frequency band. The results show that the texture indices for apples were higher than those for persimmons and pears. It means that the level of sound produced by fluctuation of the samples was higher over the determined frequency bands for apples than for the others. At the band of 2240 to 3200 Hz, note that the levels of apples and persimmons were markedly higher than that of pears. In Fig. 7 (b) the texture indices were normalized by the total amount of indices (total amount = 100) over the frequency bands to characterize the frequency dependency of the texture indices of the fruit samples. The normalized indices show significant difference among the fruit samples above 4480 Hz.

4. Discussion

The device developed for measuring food texture mimics the initial bite with the front teeth. It allows direct measurement of food texture, solving the problem that some parts of the texture information could be lost in the case of recording the mastication sound as stated in the Introduction. We used a piezoelectric sensor, which has good sensitivity and a response over a wide frequency range. The dynamic range of the piezoelectric sensor covered the full audio frequency range (Fig. 3a). The frequency range of the sound for crisp products was reported to be up to some

10-12 kHz (Vickers et al., 1976; Lee et al., 1988; Al Chakra, Allaf & Jemai, 1996). Therefore, the dynamic range of our piezoelectric sensor should be sufficient for measuring food crispness. Furthermore, De Belie, De Smedt and De Baerdemaeker (2000) stated that the higher frequency could be important because a logarithmic scale can characterize human hearing. In this case, piezoelectric sensors should be advantageous for their wide frequency response. In addition, we made efforts to reduce the background noise because the signals produced by the fracture of some food samples were very small. The silicone oil cylinder connected to the conveying pump was expected to produce less noise than that driven by an electric motor or an air-driven pump.

Signals obtained with our device contain information related to the food texture. The signals resembled those of mastication sound data taken by others (Vickers et al., 1976; Vickers, 1991) using a microphone. However, our data are more informative because data in some frequency ranges can be lost during recording mastication sounds. It is important to analyze the obtained signals to extract the information that represents the food texture. To achieve this, we used the obtained data to quantify food texture using an algorithm developed by Taniwaki et al. (2006). The normalized texture indices (Fig. 7b) made it possible to compare the texture of different food samples.

Other studies have used the mastication sound amplitude (Drake, 1965), the mean sound pressure (Seymour et al., 1988), the sound duration (Edmister et al., 1985; Al Chakra et al., 1996), and the number of sound bursts (Vickers et al., 1976; Edmister et al., 1985; Vickers, 1987). The sound frequency is also useful for differentiating between crisp and crunchy products, as stated by Dacremont (1995). The most widely used frequency analysis method for food texture is the fast Fourier transformation (FFT) (Lee et al., 1988; Seymour et al., 1988). However, FFT analysis is not appropriate for our data, for example, that shown in Fig. 6. Such signals are in a very short time period. Therefore, the frequency resolution is limited. Furthermore, such signal's FFT spectrum characteristics might be unclear because the signals are non-periodic. We developed the octave multi-filter to overcome such problems (Fig. 2). This is also an analysis method in the frequency domain.

One problem of our device is the piezoelectric sensor's detection range. Figure 3 (a) shows that the discoidal type sensor covers the full audio frequency range in the high frequency region, but small fluctuations are apparent below 1 kHz. For the piezoelectric film, the frequency response was better than that of discoidal type in the low-frequency region (Fig. 3b). However, this type was not good in the high-frequency region above 6 kHz because of its resonances. Therefore, future efforts should be made to obtain a good response for the discoidal type sensor in the low-frequency region. This might be achieved through the use of a multilayered piezoelectric sensor. We also noticed that the frequency response of the piezoelectric sensor depended strongly on the bonding condition. We used epoxy adhesive to bond the piezoelectric sensor to the aluminum piston. It was difficult to obtain exactly the same bonding condition allowing reproduction of the same frequency response of the piezoelectric sensor. In addition, a different type of probe might be necessary for different kinds of food samples. For example, a thin knife edge probe might be preferable for green onions, which are rich in fibrovascular tissues.

Our device should be useful for studying food texture. For full understanding of food texture, Tesch, Normand and Peleg (1996) stated that there must be an understanding of how mechanical failure occurs as well as of the resulting sound waves that occur with this failure. Furthermore, few researchers have studied relationships between the physical, sensory and structural components of crisp products (Duizer, 2001). Our device should also contribute to solving such problems by investigating physical and the structural components of crisp food. In relation to food structure, microscopic studies can be performed using our device. Using the probe speed and the data sampling rate, we can calculate the probe's spatial resolution. That resolution was calculated as 0.28 μm with a 22 mm s^{-1} probe speed and 80 kHz sampling rate. Typical sizes of a plant cell and a cell wall are respectively about 100 μm and 1 μm. Therefore, it might be possible to detect vibrations or sounds produced by the fracture of each cell and to measure the cell-wall strength, which should be responsible for food texture.

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Figure Captions

Fig. 1.

Device for measuring food texture and the system diagram. Texture signals were taken by inserting the probe into a sample and by detecting vibrations caused by the sample fracture. The device has a 3-mm-thick and 10-mm-diameter piezoelectric sensor. The 30-mm-long, 5-mm-diameter stainless steel probe has a conical tip.

Fig. 2.

The octave multi-filter developed using the LabVIEW program. Frequency bands were up to 25.6 kHz, as determined by an octave scale to cover the full audio frequency range.

Fig. 3.

Frequency responses of the piezoelectric sensors: (a) 3-mm-thick, 10-mm-diameter discoidal type, and (b) 0.4-mm-thick, 20-mm-diameter thin film type. Measurements were taken using a laser Doppler vibrometer and converted to displacement data.

Fig. 4.

The probe design concept. The probe resonance should be well above the frequency range of interest because it markedly distorts the signals. In our case, the frequency range of interest was the full audio frequency range (up to 20 kHz).

Fig. 5.

Estimation of the probe resonance for its various diameter and length. The lowest lateral mode frequency was calculated assuming that the probe was an aluminum cylinder.

Fig. 6.

Typical signals obtained using the device. Signals generally consist of near-random alternation of amplitude. This example was taken with an apple sample.

Fig. 7.

Calculated texture indices for apples, persimmons and pears (a) and the normalized texture indices (b). The texture indices were calculated for each frequency bands using the filtered texture signal data. Vertical bars represent SE (persimmon, n = 21; apple, n = 15; pear, n = 21).

Fig. 1, Taniwaki

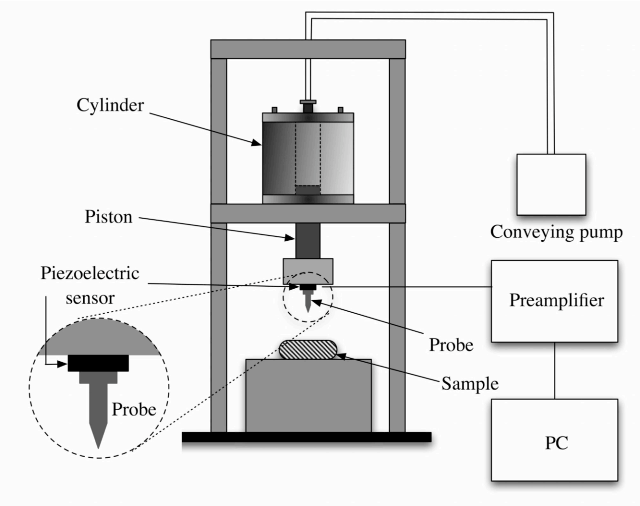


Fig. 2, Taniwaki

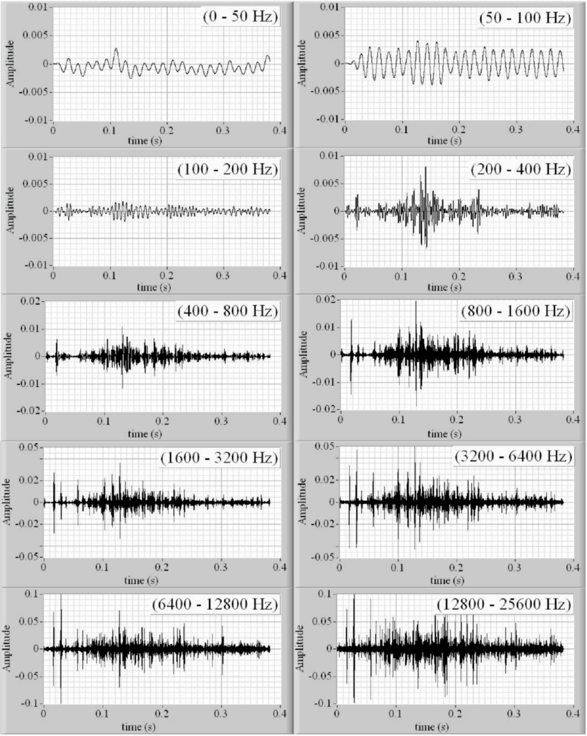


Fig.3, Taniwaki

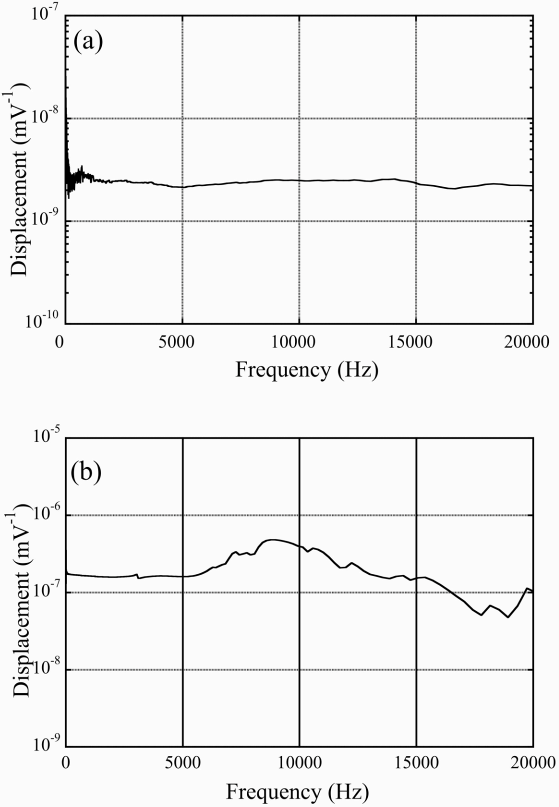
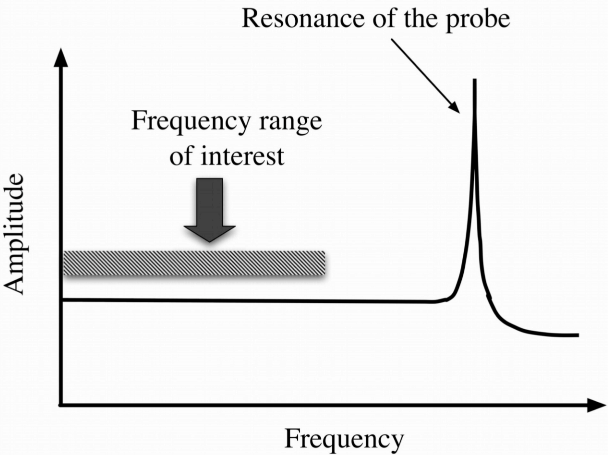


Fig.4, Taniwaki



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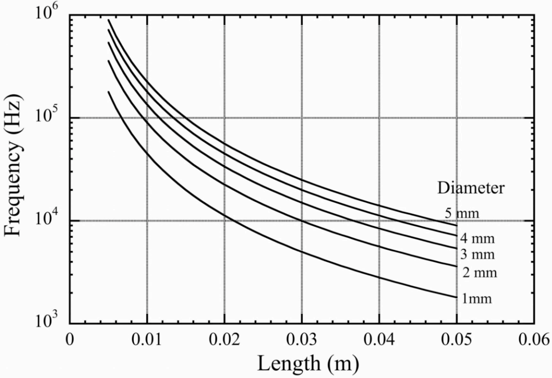

Fig.6, Taniwaki

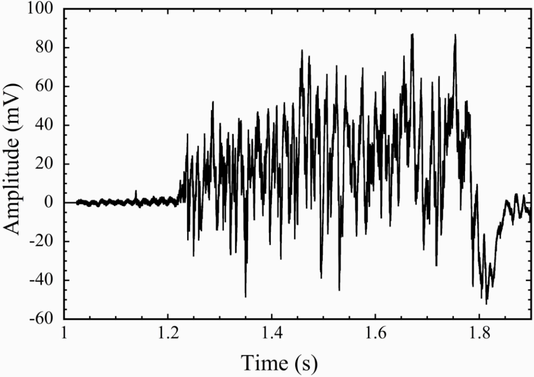

Fig.7, Taniwaki