Relationship between Food Hardness and Frequency Response Using Swept-Sine Technique

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***Abstract*— Swept-Sine technique, which can measure impulse responses even in noisy conditions, was investigated for inexpensive, nondestructive, and instantaneous evaluation of food hardness. Jelly samples with hardness variations corresponding to gelatin content and avocados that softened with aging were used as samples. A logarithmic sweep sound was input to the samples through earphones. The sound wave passing through the sample was measured with a microphone. The impulse response of the sample was obtained by convolution integration of the input signal and the sound output from the sample. The Fourier transform was applied to the impulse response to investigate the relationship between the calculated frequency response and hardness. The amplitude and frequency of the peak of the frequency response tended to increase as the hardness of the sample increased. This suggests the possibility of nondestructively measuring the hardness of vegetables and fruits.**

Keywords*— *Swept-Sine technique, Ripening, Food hardness, Impulse response, Frequency response

I. INTRODUCTION

As fruits ripen, their firmness, taste, and color change over time, but determining the exact degree of ripeness with the human eye is challenging. Current methods to accurately measure texture, such as texturometers, are destructive. Consequently, many studies have focused on using vibration and sound to monitor ripening progress without damaging the sample. One approach involves using an accelerometer and a vibration table, but this requires large equipment. Alternatively, researchers have explored predicting food hardness and ripeness by analyzing the frequency response of acoustically forced vibrations in fruits and vegetables, induced either by striking with a stick [1] or using a speaker [2][3][4][5][6][7]. However, environmental noise affects sound and vibrations captured by microphones [1][2][3][4][6][7] and laser Doppler vibrometers (LDV) [5][8], and noise affects the frequency response obtained through the Fourier transform of the measured sound. Therefore, it was difficult to use in noisy environments such as factories and retail stores.

To address these issues, this study proposes using the Swept-Sine technique for measuring frequency response related to food hardness. Swept-Sine technique can stably measure frequency response even in noisy environments, and while it has been used to measure in noisy spaces [9], its application to food products remains underexplored. This study confirmed the relationship between frequency response measured with the Swept-Sine technique and sample hardness.

II. EXPERIMENTAL METHOD

A. Frequency response measurement using swept-sine technique

This study aims to measure the acoustic frequency response of food products using the Swept-Sine technique. This method, proposed by Farina [10], measures the impulse response with a signal that varies exponentially from lower to higher frequencies and has a high signal-to-noise ratio. Fig. 1 illustrates the experimental system and frequency response measurement flow using the Swept-sine technique.

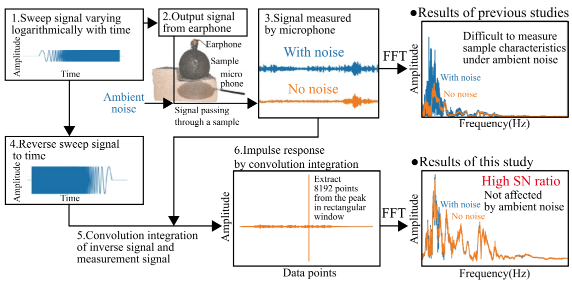

Fig. 1. Frequency response of food products using the Swept-sine technique

The sweep signal is played back through an earphone (EV-000, Daiso Industries Co., Ltd.) that connects to a laptop computer (dynabook R73, TOSHIBA). The earphone is secured to the sample with double-sided tape, and the sound passing through the sample is collected by an omni-directional microphone (MM-MCU06BK, SANWA SUPPLY INC.). A styrene foam stand is constructed to embed the microphone and prevent the sample from rolling.

Equation (1) represents the generated exponential sine sweep signal equation.

$$x(t) = \sin\left(2\pi f_{start} T \frac{\left(\frac{f_{end}}{f_{start}}\right)^{\left(\frac{t}{T}\right)} - 1}{\log\left(\frac{f_{end}}{f_{start}}\right)}\right) \quad (1)$$

where f_{start} is the start frequency of the sweep, f_{end} is the end frequency of the sweep, T is the duration of the sweep, and t is the time. The sampling rate was 48 kHz, the duration T was 60 seconds, the start frequency f_{start} was 1 Hz, and the end frequency f_{end} was 20 kHz. Equation (2) defines the inverse filter equation.

$$y(t) = x(T - t)\frac{\left(\frac{f_{end}}{f_{start}}\right)^{\left(\frac{t}{T}\right)}}{T} \quad (2)$$

Here, $x(T - t)$ denotes the time-reversed signal of the exponential sine sweep signal given by equation (1). The purpose of multiplying by $(f_{\text{end}} / f_{\text{start}})^{(t/T)} / T$ is to correct the exponentially increasing frequencies on the time axis. Since the frequency of the sweep signal increases exponentially with time, the low-frequency components dominate, and the high-frequency components are very short. Consequently, the amplitude-uncorrected impulse response will have smaller amplitudes in the high-frequency components compared to the low-frequency components, resulting in an uneven overall frequency response.

The impulse response is obtained by convolving this inverse filter with the response of the generated sine sweep signal. Although the sine sweep signal is prone to non-linear distortion, Farina's method with this exponential sweep signal shows nonlinear distortion before the peak of the measured impulse response. This feature allows for separation by removing the time domain before the peak of the impulse response. In this research, the peak is set as the starting point of a rectangular window, and 8192 points were extracted after the peak for FFT. Usually, the measured impulse response is peak-normalized before performing FFT. The implementation of this program uses Python's sounddevice library to output the generated signal from the headphone terminal and at the same time save the signal from the microphone terminal to the PC. The measured signal contained both ambient noise and sample characteristics. To remove noise, this process yields an impulse response with a high signal-to-noise ratio, giving us the frequency response of the sample.

B. Experimental Samples

The goal of this study is to explore the connection between frequency response and food hardness using the Swept-sine technique. To achieve this, two experiments are conducted: the first focused on gelatin samples with controlled hardness (Experiment 1), while the second involved avocados that softened as they ripened over time (Experiment 2). Experiment 1 prepared gelatin samples by adding 7.5 to 20 grams of gelatin (Morinaga cook gelatin, Morinaga & Co., Ltd.) to 100 ml of hot water in a 300 ml plastic cup, resulting in a gelatin concentration of 7.0% to 16.7%. The samples are then refrigerated for about 12 hours, removed from the cup, and brought to room temperature. Finally, the frequency response is measured using Swept-sine technique. Experiment 2 use green, relatively unripe avocados from Mexico, which were purchased at a supermarket. The frequency response of the avocados are measured every 30 minutes after purchase using Swept-sine technique.

III. Experimental Results

Fig. 2 illustrates the frequency response for various gelatin samples, each demonstrating a distinct frequency response based on gelatin content.

It was observed that higher gelatin content resulted in increased hardness. For example, Sample containing the highest gelatin content (20 g, 16.7% concentration), exhibited a peak around 1200 Hz. As gelatin concentration decreased to 13.0% (15 g), 9.1% (10 g), and 7.0% (7.5 g), Sample became progressively softer and more brittle, with the resonance frequency of the observed peak decreasing

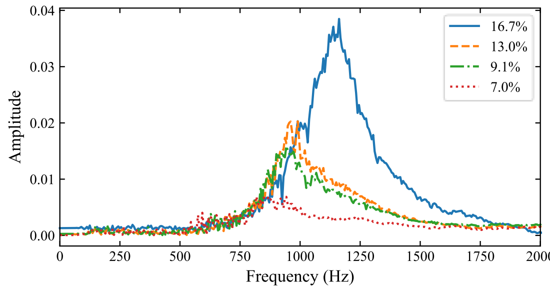

Fig. 2. Acoustic frequency response of gelatin at different concentrations

accordingly. The amplitude of resonant frequency also decreases. Equation (1) can be employed to represent the resonance frequency at which this peak occurs [3].

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{3}$$

Equation (3) consists of the hardness k of the sample and the mass m of the sample. The equation demonstrates that as a sample becomes softer, k decreases, leading to a reduction in the resonance frequency (f) where the peak appears. In this experiment, as the gelatin content decreases, k also declines. Since the samples share the same volume, the mass (m) is greater for the harder sample containing a larger amount of gelatin. Although the resonance frequency (f) decreases as mass (m) increases, it is evident that hardness (k) has a more significant impact on the frequency response than mass (m) in this experiment.

Fig. 3 presents the relationship between elapsed time and frequency response of avocados in Experiment 2.

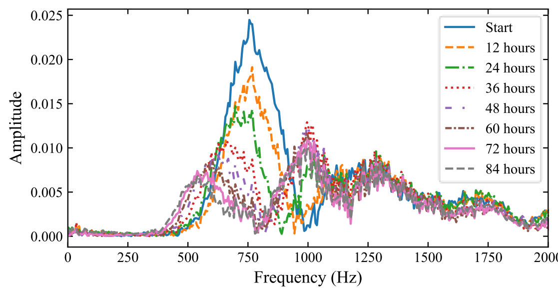

Fig. 3. Acoustic frequency response of avocados at different elapsed times

In the case of avocado, unlike gelatin, several resonance frequency peaks were identified. At the beginning of the experiment, they are found at 750 kHz and 1250 kHz. The lower peak (f_2) at 750 kHz, the resonant frequency decreased as the elapsed time increased. This is thought to be due to the softening of the avocado over time. This trend is consistent with the results of Experiment 1, in which decreasing the gelatin content softened the sample and decreased the resonance frequency and amplitude.

On the other hand, another peak (f_3) also appeared at 1 kHz from 24 to 84 hours. This is a result that could not be confirmed for gelatin. The difference in the vibrational properties of gelatin and avocado suggests the influence of these composite structures. Because gelatin has a homogeneous structure, only a shift of the lower peak position was observed. But Avocados have a composite structure of seeds and edible parts. At the beginning of the experiment, the edible part of the avocado is hard and shows elastic properties similar to those of the seed of the avocado. However, due to changes caused by ripening, the edible part becomes softer and is identified as a peak on the low frequency side. Although, the seeds, which remain hard, are thought to be identified as a 1 kHz peak. Thus, it is thought that several resonance frequencies can be identified in samples with composite structures.

Also, Similar to the present study, a non-destructive acoustic vibration method was used to sort out whether the peaches were properly grown or not [6]. The ratio of the resonance frequency at 1 kHz to the resonance frequency on the low frequency side can be used to detect if the seeds are splitting and growing inside the peach as it grows into a tree. If the seed is splitting, the ratio of the frequencies of the two peaks increases significantly. This can be explained by the influence of the edible part and the state of the seed.

There are also reports of non-destructive acoustic assessment of the amount of rot in the center of Pears [7]. When uncorrupted, f_3 appeared between 0.8 and 1 kHz. The f_3 frequency decreased as the central rotten volume increased. We also found that f_2 (0.5 to 0.7 kHz) decreases as core decay volume increases. From this, f_3 changed when the spoiled volume was less than 5%, and f_2 changed when it was 5% or more. Pears rot and soften from the core, thus reducing f_3 and f_2. However, the core of the avocado remained a hard seed and the edible part around it softened, so f_3 did not change and only f_2 decreased. These reports are also consistent with the results for avocados in this study. f_2 indicates the hardness of the edible portion due to the degree of ripeness of the avocado.

In summary, Swept-sine technique confirmed that the resonance frequency and the amplitude decrease as the gelatin sample in Experiment 1 and the avocado sample in Experiment 2 soften. Swept-sine technique is highly resistant to noise and can stably measure the frequency characteristics related to food quality, so it should be more widely used.

IV. CONCLUSION

Using Swept-Sine technique, which measures acoustic properties with a high signal-to-noise ratio even in noisy environments, we demonstrated the relationship between food hardness and frequency response, which varies with the amount of gelatin and avocado ripeness. Since gelatin is a homogeneous sample, it has one resonance frequency, and avocado consists of seeds and pulp, so we were able to confirm multiple resonance frequencies. In both gelatin and avocado samples, the amplitude and frequency of the peak of the frequency response tended to increase as hardness increased.

Many studies have been reported to acoustically assess the firmness of fruits and foods, but none have used the sweep sine technique. It is an excellent non-destructive measurement method that can instantly measure the hardness of food even in noisy environments. It is therefore suitable for use in food production plants and consumer retail outlets. Although the equipment required for measurement is inexpensive, we aim to develop a smartphone application using built-in speakers and microphones in the future. This innovation would provide an accessible and cost-effective means of measuring food hardness.

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