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Non-destructive firmness assessment of apples using a non-contact laser excitation system based on a laser-induced plasma shock wave

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ABSTRACT

Various indexes have been used to assess the ripeness of fruit, including peel color and firmness because added value is given to fruit when grade selection is determined objectively. In this paper, we realize a non-destructive firmness assessment for apples by means of a non-contact vibration test method. We investigate their natural frequencies and vibration mode shapes because these factors influence the ${}_0S_2$ mode, which is related to firmness. A laser-induced plasma shock wave generated with a high-output Nd:YAG pulsed laser is applied to apples as an excitation force. Firmness is assessed with this non-contact and non-destructive method using the apple's vibration response spectra measured with a laser Doppler vibrometer. The effectiveness of this method is experimentally demonstrated through assessments of apples' firmness, identification of the vibration mode shapes, and a follow-up survey on the flesh firmness of apples during storage.

1. Introduction

Various indexes show the ripeness of fruit, including peel color, taste, aroma, and firmness. By objectively assessing these indexes and carrying out grade selection, it should be possible to add value to fruit. To date, many ripeness assessment methods have been proposed based on the characteristics of the concerned fruit (Abbott, 1999). Simple methods used in fruit sorting facilities include firmness and sugar content measurements, which consist of pushing a plunger into the flesh and measuring the soluble solids contained in the juice, respectively. Although these methods allow the quality of the fruit in question to be directly measured, they are destructive. In addition, in fruit with greater individual differences, the decrease in sorting accuracy is a concern. Ideally, total quality assessments should adopt non-destructive tests.

Non-destructive tests that evaluate the ripeness of fruit can be roughly divided into three categories: methods employing biochemical, optical, or vibration properties. Among the approaches using biochemical properties, one method uses an electronic nose or gas chromatography to detect the flavor components extracted from the peel (Beaulieu and Lea, 2003; Saevels et al., 2004; Lebrun et al., 2008; Benedetti et al., 2008; Li et al., 2009; Torri et al., 2010; Oms-Oliu et al., 2011; Janzantti and Monteiro, 2014). This method, which only covers a small variety of fruit that emit a strong odor, is still under development. Among the methods based on the optical properties, one assesses the color of the peel by irradiating visible light onto the fruit, while another estimates the sugar content by irradiating near-infrared light (Kawano et al., 1992; Lancaster et al., 1997; Schmilovitch et al., 2000; Noh and Lu, 2007; Peng and Lu, 2007; Qin and Lu, 2008; Bureau et al., 2009; Pérez-Marín et al., 2009; Intaravanne et al., 2012). Although these methods have practical applications, they are difficult to apply to fruit whose surfaces do not show color changes or do not transmit light. Exciting fruit by an exciter or a hammer is one method to assess firmness using the vibration properties (Cooke, 1972; Yamamoto et al., 1981; Armstrong et al., 1990; Huarng et al., 1993; Muramatsu et al., 1996; Duprat et al., 1997; Schotte et al., 1999; Hung et al., 1999; De Belie et al., 2000; Flitsanov et al., 2000; Terasaki et al., 2001; Shmulevich et al., 2003; Motomura et al., 2004; Molina-Delgado et al., 2009; Taniwaki et al., 2009, 2010; Grimi et al., 2010; Iwatani et al., 2011; Abbaszadeh et al., 2013; Foerster et al., 2013; Macrelli et al., 2013; Zhang et al., 2014), but this contact method can only be applied to fruit with thick peels or those whose peels do not change color.

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The firmness of a fruit is considered a more important index to assess ripeness than the sugar or acid content because firmness is significantly related to ripeness. However, the use of contact devices such as exciters and hammers requires fruit to be examined individually, which is unrealistic as a post-harvest ripeness assessment (ripening management) of all fruit. In addition, this method cannot be applied to small, light, or soft fruit as it may induce damage. Although an approach that uses a non-contact device (Muramatsu et al., 1996) with an embedded speaker is under study, it has numerous limitations, including those related to the exciting position, difficulty generating impulse sound sources that allow the dynamic characteristics to be evaluated over a broadband in a short time, and the necessity of devices (speakers and cables) to generate sound sources.

In this paper, we perform a non-destructive assessment of the firmness of apples by measuring their natural frequencies through non-contact vibration tests in which the shock wave generated by a laser-induced plasma (LIP) (hereafter referred to as the "LIP shock wave") is turned into an impulse excitation. Although we can realize an ideal point excitation using another laser excitation method based on laser ablation (LA) (Kajiwara and Hosoya, 2011; Hosoya et al., 2012, 2014, 2016a,c,d, 2017; Huda et al., 2013), the LA-generated excitation induces sub-millimeter-sized damage onto the laser-irradiated surface of a fruit. Because an apple's firmness influences the ${}_0S_2$ mode of the natural frequencies and the vibration mode shapes (Cooke, 1972; Huarng et al., 1993; Terasaki et al., 2001), we investigate these characteristics.

One advantage of our system is that traditional exciting devices (e.g., exciters or hammers) are replaced by a non-contact and non-destructive LIP shock wave. LIP is a kind of plasma generated by condensing a high-output pulse laser, and if factors such as the surrounding environment (temperature and humidity), the irradiated medium, and the laser fluence are identical, the LIP shock wave shows a high reproducibility. Previous studies (Oksanen and Hietanen, 1994; Georgiev et al., 2011; Hosoya et al., 2013, 2016b; Huda et al., 2014; Bahr et al., 2015; Eskelinen et al., 2015; Zhang et al., 2015) have reported using a LIP shock wave in an acoustic test as a point sound source or a vibration test as a point excitation force. However, this method has yet to be applied to assess firmness of fruit. Similar to the previous studies (Terasaki et al., 2001; Motomura et al., 2004; Taniwaki et al., 2009, 2010; Iwatani et al., 2011; Foerster et al., 2013; Abbaszadeh et al., 2013; Zhang et al., 2014), we use a laser Doppler vibrometer (LDV) for the response measurements. In our system both the input and output measurements are performed with a non-contact method by adopting a non-contact excitation as an input with a LIP shock wave, which has been considered difficult to date.

In this experiment, the firmness of apples is assessed. First, the natural frequencies of apples are measured with our system to determine the appropriate conditions (the position of the LIP shock wave generation and the magnitude of the laser pulse energy necessary for LIP shock wave generation). Second, the relationship between the measured natural frequency and the vibration mode shape is examined. Third, the changes in flesh firmness and the natural frequencies of stored apples are studied to demonstrate the validity of our method.

2. Firmness assessment system of apples using a LIP shock wave

Fig. 1 shows our firmness assessment system of apples using a LIP shock wave. The laser beam from a high-output Nd:YAG pulsed laser (Surelite III-10, Continuum Inc., wavelength: 1064 nm, laser beam radius: 4.75 mm, pulse width: 5 ns, maximum output: 1 J, and radial divergence angle: 0.25 mrad) installed on the optical bench was condensed with a plano-convex lens (focal length: 100 mm) to generate a LIP shock wave near the desired excitation point on the apple. A LIP shock wave is generated when the LIP expands into the periphery at a high speed. The laser fluence I [W/m^2] necessary to form LIP in air can be described by Eq. (1) (Georgiev et al., 2011; Hosoya et al., 2013) as

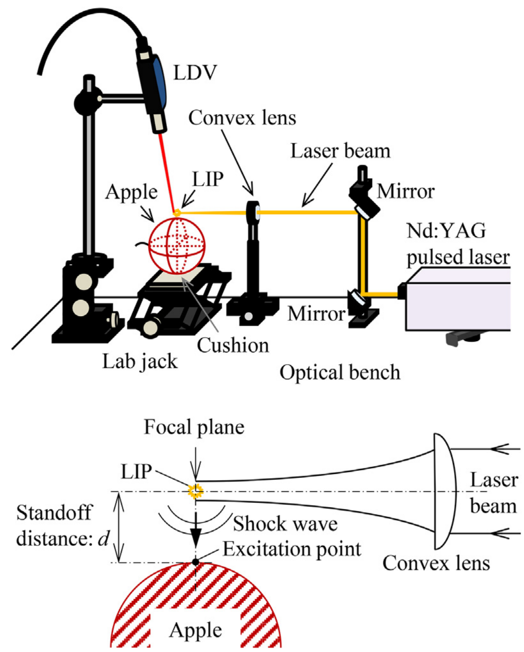

Fig. 1. Non-contact and non-destructive firmness assessment system of apples using a LIP shock wave as the input.

$$I = \frac{E}{ST} \tag{1}$$

where E is the laser pulse energy [J], T is the pulse width of the laser [s], and S is the area irradiated by the laser [m^2]. Because the threshold of LIP in air is $I \geq 10^{15}$ W/m^2, we adjusted the E and S values so that they reach this threshold. To generate LIP in air, we used a plano-convex lens to focus the laser beam radius from 4.75 mm to 25 μm. The laser fluence at the focal plane rose from 2.65×10^{12} W/m^2 to 9.57×10^{16} W/m^2, exceeding the LIP threshold. If we generate LIP above the desired excitation point of the apple, the lens position or the focal length of lens against the apple should be properly adjusted at the focal plane (Fig. 1). The responses of the apples measured in a non-contact manner with LDV (NLV-2500-5, Polytec GmbH) were recorded with a spectrum analyzer (A/D: NI PXI-4462, National Instruments Co., Software: CAT-System, CATEC Inc.).

3. Non-destructive firmness assessment of apples

3.1. Test pieces

To consider individual differences, we used eleven apples of the cultivar "Sun Fuji" (Yamagata Prefecture, Japan) as test pieces to assess the firmness under various experimental conditions (Table 1). Fig. 2 shows the excitation points and measurement points on the apples (see Fig. 1). Apples A and B were used to clarify the relationships between an apple's vibration response, the magnitude of the LIP shock wave, and the distance between the LIP generation point to the excitation point on the apple (hereafter, the "standoff distance"). Apple C was used to identify an apple's spheroidal (elliptical) vibration mode shapes, which are associated with firmness (Huarng et al., 1993; Terasaki et al., 2001). Apples D–K were used to investigate the change in the firmness during