13th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering
Zürich, Switzerland (13.-15. June 2021)

UVP applied for Doppler scanning of fruit-internal structures and its working principle

Yuichi Murai[1], Taiki Yoshida[2], Hyun Jin Park[1], and Yuji Tasaka[1]

[1] Laboratory for Flow Control, Hokkaido University, N13W8, Sapporo, Hokkaido, 060-8628, Japan
[2]National Institute of Advanced Industrial Science and Technology, Tsukuba Central 3, 1-1-1, Umezono, Tsukuba 305-8563, Japan

The Inner structures of fruits are visualized by UVP instrument, i.e. reflection signals of ultrasound pulse. A target is submerged in a rotating water container so that a single ultrasonic transducer obtains echo intensity and Doppler velocity profiles as a function of rotating angle. By integrating the echo and Doppler signals over several rotations, the inner structures are successfully reconstructed as two-dimensional scanned distributions. While echo intensity measures stiffness of a target surface, Doppler image captures the inner structure with superficial phase shift that occurs due to moving acoustic property. We examine the applicability of the method to a kiwi, an apple, and a tomato, and find that gas cavities, solid-state seeds, and liquid-state portions inside these fruits being visualized.

Keywords: Pulse Doppler method, Doppler imaging, Fruit, Non-destructive diagnosis, Food industry

1. Introduction

Owing to the increasing worldwide consumer demand for high-quality fresh fruit, rapid evaluations of the maturity and quality of fresh fruits require a breakthrough in the development of a nondestructive, reliable, and noninvasive methodology. Sensing the inner structures of fruits together with evaluating the pulp hardness is important to this purpose. In the field of food engineering, sensing techniques have been developed using ultrasonic waves, magnetic resonance imaging (MRI)[1-3], computed tomography (CT)[4-5], optical coherence tomography (OCT) [6-8], and a laser Doppler vibrometer (LDV)[9]. MRI measurement systems require a huge facility to obtain a visualized image, and they may, therefore, not be suited to practical use. For the same reason, CT using X-rays should be disregarded as an option. OCT can realize higher spatial resolution of $O(10\mu m)$ adopting near-infrared radiation; however, the maximum transmitting distance of the radiation is limited to $O(1mm)$ in the application to botanical tissues. The LDV can estimate the hardness of pulps obtained by minute vibrations, and is a point measurement system. Thus, only the local point of the target can be estimated. Mizrach[10-12] reported an evaluation method for determining fruit tissue properties using a high-power and low-frequency ultrasound system. The system, however, determines the properties usually from a single measurement point and increasing the number of measurement points requires additional pairs of an ultrasonic emitter and receiver. Generally, fruit pulps have heterogeneous tissues, such as parenchyma cells, fiber cells, and stone cells, which have different properties owing to differences in fiber orientation and moisture content. In these cells of fruit and vegetables, which have an inhomogeneous microstructure, the depression of ultrasonic propagations is higher than that in homogeneous media. Thus, a one-directional or one-point ultrasonic measurement may have obvious disadvantages. The development of the multidirectional sensing of fruit properties in a simple and convenient way is desirable.

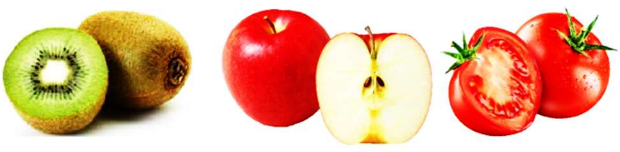
To realize the multidirectional sensing of inner structures of fresh fruit using the UVP, a rotating cylinder system is used on the basis of our understanding of ultrasonic spinning rheometry[13], where the test fruit is rotated by a cylindrical vessel and passes through a single ultrasonic propagation line. This realizes multiple sensing lines for the test fruit without using multiple sensors or rotating a sensor. To recognize inner structures, the Doppler velocity is used in addition to basic echo intensity information. The Doppler velocity is obtained as the velocity of ultrasonic reflection particles dispersed in fluid media, and it reflects local acoustic characteristics. Murai et al.[14] found that there are pseudo-low Doppler velocity regions near the interfaces of bubbles flowing in fluid media because of the interference of ultrasonic waves around the interface. In our previous paper (Yoshida et al.[15]), we we investigated the feasibility of applying the UVP to the visualization of inner structures of fresh fruit, especially O (mm) in size comparable to the wavelength of the ultrasonic wave. This was termed ultrasonic Doppler–echo visualization.

In the present paper, working principle of the ultrasonic visualization is revisited. Points of investigation are (1) how the two-dimensional inner structures can be reconstructed by a single path of ultrasound pulse, (a) what the echo intensity profile means and (2) why Doppler velocity profile corresponds well to the inner structure of a fruit that is mostly in solid state. Namely, we purpose to understand the working principle od the Doppler-echo visualization technique while visualization always works properly for various types of fruits.

2. Measurement Method

2.1 Target of Visualization

As shown in Fig. 1, we chose (a) kiwi, (b) apple, and (c) tomato as a target of visualization. Kiwi is known as a fruit covered by a thick hard skin so that inner condition is hardly imaginable only by touching the surface. Apples involve gas cavities and relatively large seeds in the core. Tomato consists of liquid-state part and hard tissue in the core. In food industry, day-change of the inner structure, which is hardly visible from outside, needs to be monitored to optimize forwarding time control for consumers. The visualization also helps with effective combination with other food materials such as bread and rice. For instance, tomato of thick skin with less gel parts is demanded for sandwiches producers for long lasting in sell.



(a) Kiwi (b) Apple (c) Tomato

Fig. 2 Target of ultrasonic visualization

2.2 System Configuration

Experiments were conducted in the open-top rotating cylinder made of acrylic resin shown in Fig. 2. The cylinder had an inner diameter of 145 mm (2R), height of 60 mm, and lateral-wall thickness of 2 mm. The cylinder was filled with a gelling suspension, test objects were put into the suspension to ensure incidence of the ultrasonic wave into objects, and the objects were placed at their initial positions.

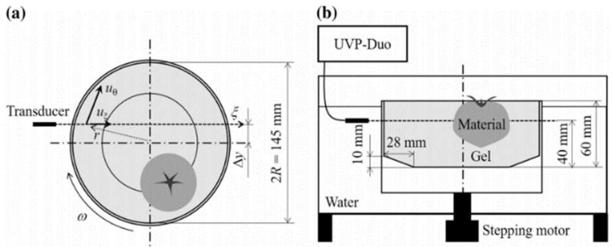


Fig. 2 Schematic diagram of ultrasonic scanning system; (a) top view, and (b) side view

The gelling suspension was made of montmorillonite powder (4.0 wt%) and NaCl solution (1.0 mol/L), and contained resin particles having a diameter of 100 µm to obtain echo information from the suspension. The cylinder was mounted at the center of a 1000 mm x 1000 mm water bath to maintain a uniform temperature at 25 C and to allow ultrasonic waves to propagate from outside the cylinder. Rotations of the cylinder were controlled by a stepping motor set with a given rotation speed X (= 2px/60). After all fluid in the cylinder reached a steady state of rigid rotation, repetitive ultrasonic emitting and receiving were performed using a UVP Duo monitor (Met-Flow S.A., Switzerland), and ultrasonic echo signals from test objects were processed using the same equipment to extract Doppler velocity information (termed the ‘‘Doppler velocity’’ hereafter). The UVP originally provided a spatiotemporal velocity distribution u(x, t) and corresponding echo intensity. To obtain the multidirectional Doppler velocity at inner structures of test objects, an ultrasonic transducer with a resonance frequency of 4 MHz and effective element diameter of 5 mm was mounted in the chamber. The corresponding measurement line was set 40 mm from the cylinder bottom with $\Delta y = 15$ mm.

Test objects were located inside the vessel at the off-center position as shown in Fig. 3. The sampling rate and spatial resolution determining the number of scanning lines were set at 66 ms and 0.74 mm during the measurement.

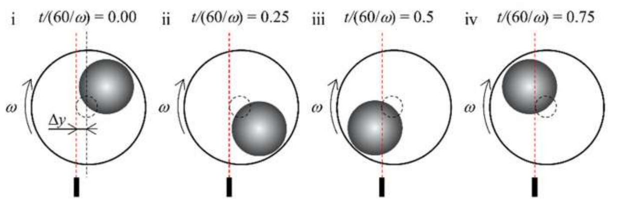


Fig. 3 Instantaneous position of a target object in rotating container relative to the ultrasound path

3. Results and Discussions

3.1 Space-time mapping

Fig. 4 shows the echo intensity distribution of a kiwi. The abscissa indicates the time, where the rotation period is 4.0 sec. The ordinate is the space from the transducer, where 0 stands for the inner wall of the cylindrical container. Red bands are the position of high echo intensity, which corresponds the surface of the kiwi. The other regions are mostly zero in average.

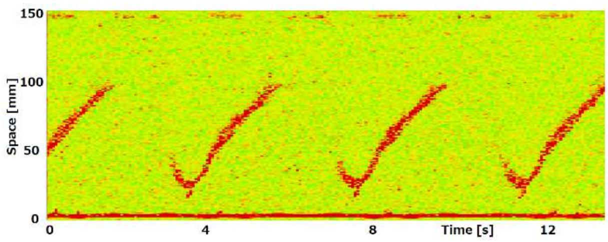


Fig. 4 Space-time map of echo intensity for a kiwi

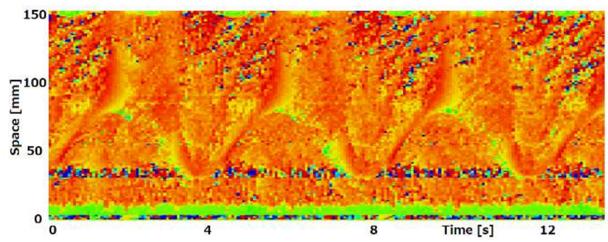
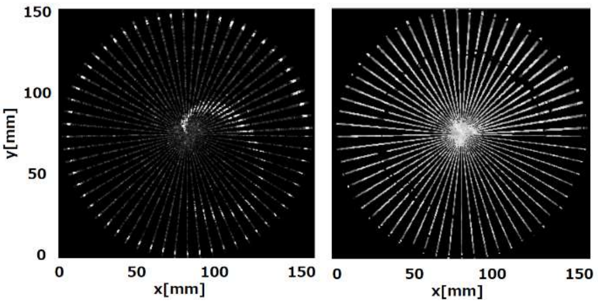


Fig. 5 Space-time map of Doppler velocity for a kiwi

Fig. 5 presents that of Doppler velocity distribution for the same kiwi, which is obtained simultaneously with echo intensity. Since the transducer is set slightly off-axis from the rotational center, Doppler velocity takes positive values inside the container. There can be seen a wavy pattern in the space-time map, which corresponds to the change in acoustic property between the inner and the outer region of the kiwi.

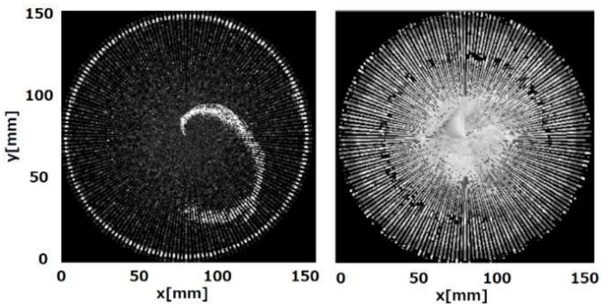
3.2 Reconstruction of the inner structure

Coordinate conversion of the signal from the space-time map to spatial two-dimensional map is performed. The conversion is realized by replacing the time axis with rotation angle, based on constant angular velocity applied.



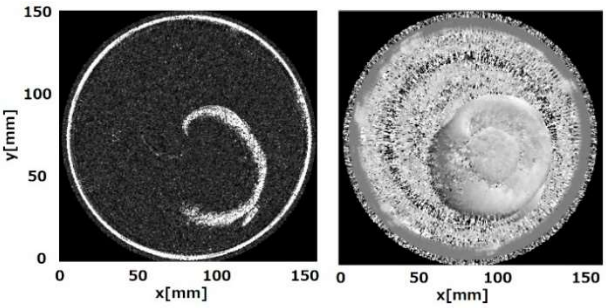
(a) Echo image (b) Doppler image

Fig. 6 One-cycle integration



(a) Echo image (b) Doppler image

Fig. 7 Four-cycle integration



(a) Echo image (b) Doppler image

Fig. 8 Sixteen-cycle integration

Fig. 6 to Fig. 8 depict how the inner structure is reconstructed with increase in the integration of cycle number. In each figure, (a) is echo image and (b) is Doppler image. Echo image clearly indicate the outline of the fruit since the surface reflects the ultrasonic pulses the most. Doppler image has some pattern including the inner region of the fruit, indicating some organized pattern of the acoustic property inside the fruit. We examined how these images are reconstructed with increase in integration cycles as shown in Fig. 9.

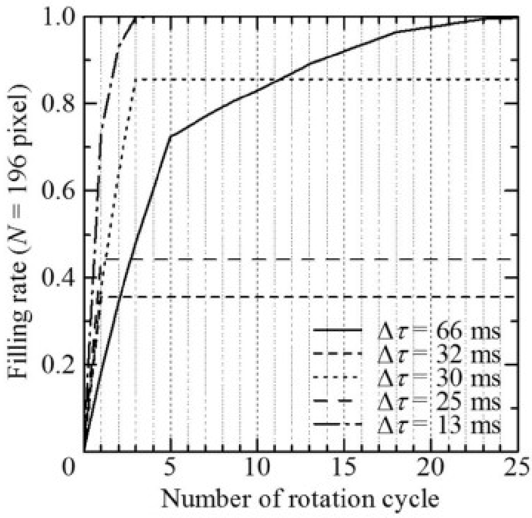


Fig. 9 Filling rate increased by integration cycles

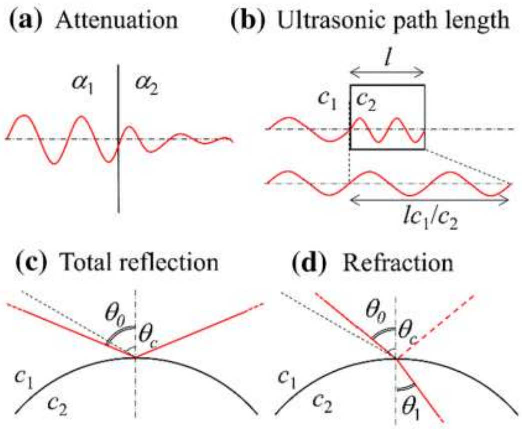


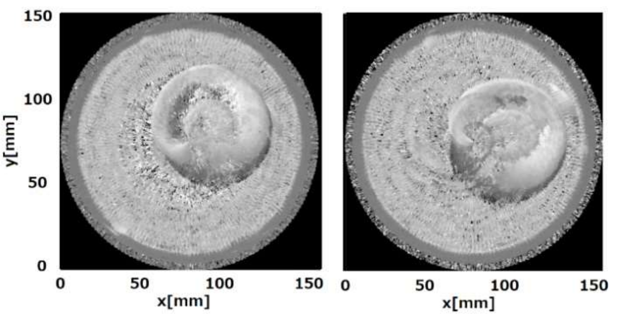
Fig. 10 Four patterns of ultrasonic pulse behavior

Fig. 10 illustrates four different patterns of ultrasonic pulse behavior, which explains the trend found in the echo image and Doppler image. For echo image, (a) attenuation inside the medium and (c) total reflection at the border of acoustic property govern the echo intensity. For Doppler image, (b) ultrasonic pulse length modified at the border and (d) refraction on the interface superficially shift the Doppler velocity, i.e. phase shift of the pulse.

3.3 Applications and interpretations

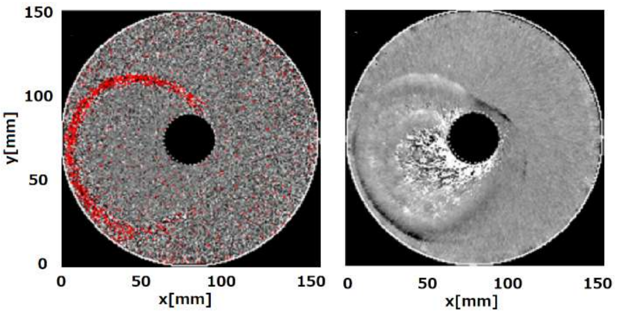
Fig. 11 compares the Doppler image of a kiwi between fresh and old states. By cutting it 10 days later, the old kiwi became soft containing gel-like part both in the near-skin layer and the core. The Doppler image of the old kiwi seems to have smoothened pattern. This is attributed to lowering of the acoustic impedance of the skin layer, expanding the pulse length.

Fig. 12 shows the case applied for a fresh apple. The echo image clearly figures out the shape of the surface. The Doppler image contains sharp fluctuation in the core region of the apple, which corresponds to the position of seeds and small gas cavity around them. In case of a tomato, as shown in Fig. 13, gel-like region and the hard-core region are clearly visualized by the Doppler imaging. In fact, we also examined the present technique for pieces of pineapple, dry-fruit tips, and tapioca particles. This will be presented in slide-show presentation in the ISUD.



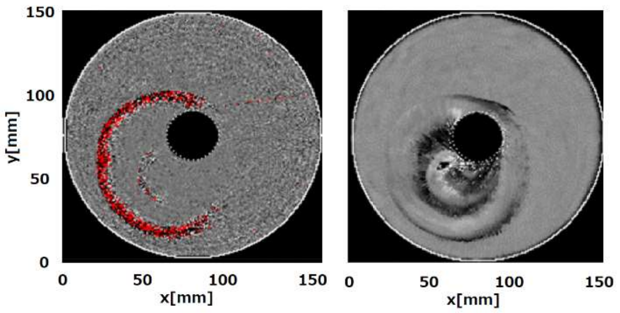
(a) Fresh kiwi (b) Old kiwi (10 days later)

Fig. 11 Comparison of Doppler images for a kiwi



(a) Echo image (b) Doppler image

Fig. 12 Visualization of an apple



(a) Echo image (b) Doppler image

Fig. 13 Visualization of a tomato

4. Summary

Functions of UVP are applied for visualizing inner structure of fruits. Echo and Doppler information are converted into two-dimensional cross section image by cyclic intergation. Both type of the image well correspond to the real structure of the fruit up to a spatial resolution of *O*(1mm). In particular, Doppler image provides rich information on the innner structure, thanks to the phase shift analysis principle of the UVP system. The feasibility has been well demonstrated, however, this will need further understanding as the technique is used for quantitative visualization in future.

Acknowledgment

This study is financially supported by Robust Agriculture Research Center, Hokkaido University. The authors thank to Prof. Koseki and Mr. Teramura, Food Processing Engineering Laboratory, Faculty of Agriculture, Hokkaido University.

References

[1] Clarka CJ, Hockings PD, Joyce DC, Mazucco RA: Application of magnetic resonance imaging to pre- and post-harvest studies of fruits and vegetables. Postharvest Biol Technol 11(1) (1997), 1–21.

[2] Saltveit ME: Determining tomato fruit maturity with nondestructive in vivo nuclear magnetic resonance imaging. Postharvest Biol Technol 1(2) (1991), 153–159.

[3] Zhang L, Michael JM: Measurement and evaluation of tomato maturity using magnetic resonance imaging. Postharvest Biol Technol 67 (2012), 37–43.

[4] Brodersen CR, Lee EF, Choat B, Jansen S, Phillips RJ, Shackel, KA, McElrone AJ, Matthews MA: Automated analysis of three-dimensional xylem networks using high-resolution computed tomography. New Phytol 191(4) (2011), 1168–1179.

[5] Staedler YM, Masson D, Scho¨nenberger J: Plant tissues in 3D via X-ray tomography: simple contrasting methods allow high resolution imaging. PLoS One 8(9) (2013) e75295.

[6] Lee C, Lee SY, Kim JY, Jung HY, Kim J: Optical sensing method for screening disease in melon seeds by using optical coherence tomography. Sensors 11(10) (2011), 9467–9477.

[7] Oldenburg AL, Chenyang X, Boppart SA: Spectroscopic optical coherence tomography and microscopy. IEEE J Sel Top Quant 13(6) 8 (2007), 1629–1640.

[8] Verboven P, Nemeth A, Abera MK, Bongaers E, Daelemans D, Estrade P, Herremans E, Hertog M, Saeys W, Vanstreels E, Verlinden B, Leitner M, Nicolai B: Optical coherence tomography visualizes microstructure of apple peel. Postharvest Biol Technol 78 (2013), 123–132.

[9] Hosoya N, Mishima M, Kajiwara I, Maeda S: Non-destructive firmness assessment of apples using a non-contact laser excitation system based on a laser-induced plasma shock wave. Postharvest Biol Tec 128 (2017), 1–17.

[10] Mizrach A: Assessing plum fruit quality attributes with an ultrasonic method. Food Res Int 37(6) (2004), 627–631.

[11] Mizrach A: Nondestructive ultrasonic monitoring of tomato quality during shelf-life storage. Postharvest Biol Technol. 46(3) (2007), 271–274.

[12] Mizrach A: Ultrasonic technology for quality evaluation of fresh fruit and vegetables in pre- and postharvest processes. Postharvest Biol Technol 48(3) (2008), 315–330.

[13] Tasaka Y, Kimura T, Murai Y: Estimating the effective viscosity of bubble suspension in oscillatory shear flows by means of ultrasonic spinning rheometry. Exp Fluids 56(1) (2015), 1897.

[14] Murai Y, Fujii H, Tasaka Y, Takeda Y:Turbulent bubbly channel flow investigated by ultrasound velocity profiler. J Fluid Sci Technol 1(1) (2006), 12–23.

[15] Yoshida, T., Tasaka, Y., Park, H.J., Murai, Y.. Teramura, H., Koseki, S: Inner structure visualization of fresh fruits utilizing ultrasonic velocity profiler. Journal of Visualization, 21 (2017), 253-265.