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Volume Measurement of Particle Layers in a Container by Using Helmholtz Resonance

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The percentage of ripened grains (PRG) is an important indicator affecting rice yield and quality, which is used for production management of rice. However, PRG can be evaluated only in test fields, because the current method of measuring PRG through quadrat sampling is time–consuming and laborious. Meanwhile, PRG can be estimated by particle density of rough rice, which is calculated by the ratio of mass to true volume of rough rice layer piled in a combine grain tank. Commercially available combines have already been equipped with the function of measuring mass of rough rice. However, the technology has not been available for measuring volume of rough rice layers in a grain tank. The objective of this study was to investigate whether volume of a rough rice layers in a container can be estimated using Helmholtz resonance. We used a closed–type cylinder resonator (volume: 770 cm^3) for measuring volume of water, glass beads having diameter of 1 mm, glass fragments having width larger than 0.7 mm, and rough rice. For glass fragments and rough rice, three filling conditions, which included loose, free fall, and dense, were tested to investigate the effect of porosity in particle layers on the volume measurement. Moreover, volume of water and particle layers estimated using resonant frequency was compared with true volume. Estimated volume had a strong linear correlation (r>0.99) with true volume for all the filling conditions and materials. On the other hand, volume was more underestimated as porosity in a particle layer increased. A possible reason for underestimating volume was that vibration energy attenuated by porosity in a particle layer decreased resonant frequency.

Key words: Glass beads, Glass fragments, Grain tank, Percentage of ripened grains, Rough rice

INTRODUCTION

The percentage of ripened grains (PRG) is an important indicator used to improve production management of rice. However, PRG can be evaluated only in test fields, because the current method of measuring PRG through quadrat sampling is time-consuming and laborious. This study focuses on estimating the PRG from particle density of rough rice during combine harvesting. The particle density of rough rice is calculated by the ratio of mass to true volume of a rough rice layer piled in a combine grain tank. Commercially available combines have already been equipped with the function of measuring mass of rough rice (Miyachi *et al*., 2014). Thus, the method of measuring volume of a rough rice layer piled in a grain tank needs to be developed to calculate the particle density.

The true volume is volume excluding porosity of a rough rice layer piled in a grain tank, and it is different from the apparent volume. We focused on the measurement of true volume using Helmholtz resonance. Nishizu and Ikeda (1995) applied Helmholtz resonance to measure volume of fruits and vegetables, such as apples, grapes, and red beans. However, to the best of authors' knowledge, Helmholtz resonance has not been applied to the volume measurement of a particle layer. Nishizu *et al*. (2017) only clarified that the Helmholtz resonance frequency measured for a particle layer decreased as the specific airflow resistance increased. Thus, the objectives of this study were to clarify the effects of particle types and porosity in a particle layer on the volume measurement and to investigate whether true volume of a rough rice layer piled in a container can be estimated using Helmholtz resonance.

MATERIALS AND METHODS

Volume measurement system

The volume measurement system consists of a closed-type cylinder resonator, a loud–speaker (NS3–193–8A, AURASOUND), an LCR meter (IM3536, HIOKI), and a PC for data measurement (Fig. 1 (a)). The volume of the cavity for piling samples is 770 cm^3. Figure 1 (b) shows dimensions of the resonator. The speaker was attached above the resonator. The electrical impedance of the voice coil of the speaker was recorded by the LCR Meter Sample Application (JP132.msi, HIOKI) when the frequency was changed by the LCR meter.

Volume estimation

The volume of a sample in an open–type Helmholtz

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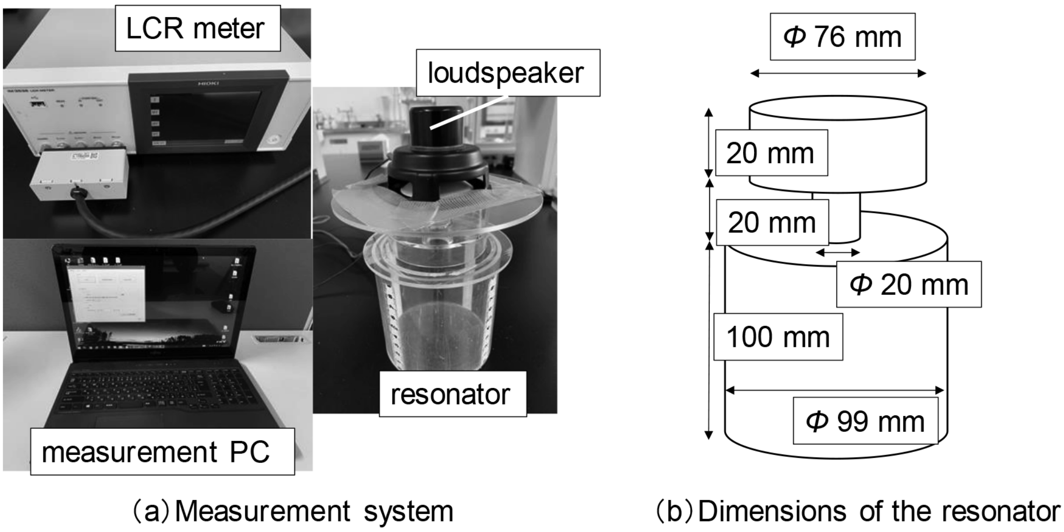

Fig. 1. Volume measurement system.

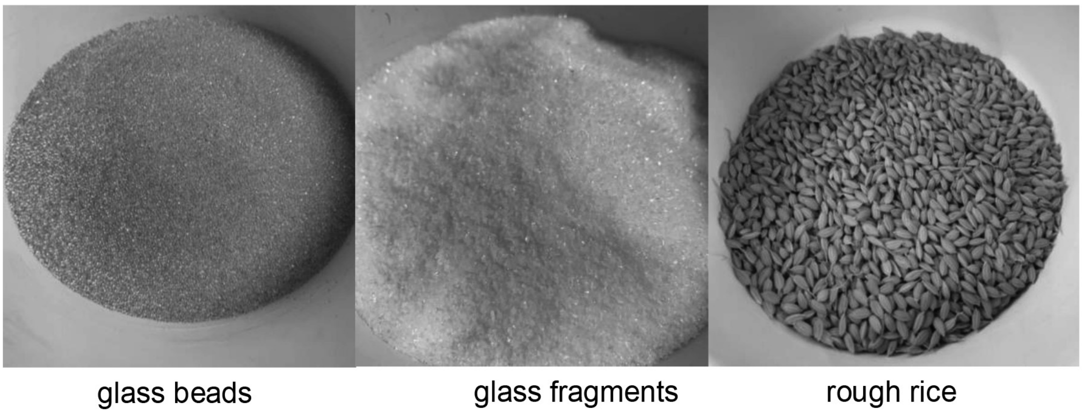

Fig. 2. Experimental samples.

resonator is estimated by the following Eq. (1) (Nishizu and Ikeda, 1995).

$$V_1 = V_0\left\{1-\left(f_0/f_1\right)^2\right\} \tag{1}$$

where f_0 is resonant frequency when the resonator is empty, f_1 is resonant frequency when a sample is in the cavity, V_0 is volume of the resonator cavity, and V_1 is volume of a sample. The resonant frequency was measured when the electrical impedance of the voice coil of the loudspeaker showed an extreme value (Nishizu *et al.*, 2005a).

Experimental samples

Experimental samples included water, glass beads having diameter of 1 mm, glass fragments having diameter larger than 0.7 mm, and rough rice (Fig. 2). The density of glass beads and glass fragments was 2.6 g/cm^3. The particle density of rough rice was 1.30 g/cm^3. The cultivar of rough rice was Akitakomachi.

Experimental procedure

A loudspeaker was driven by a signal sweeping from 100 to 200 Hz at a 0.1 Hz interval. The applied voltage was 5 V. A response to the swept signal was detected as the loudspeaker's voice coil impedance of which the extreme value corresponded to the resonant frequency.

First, we measured the resonant frequency when the resonator was empty. Next, the resonant frequency was measured when water was poured in the resonator up to 500 cm^3 with a 20 cm^3 increment. The volume and resonant frequency were measured for glass beads piled up to 800 g with a 100 g increment, for glass fragments up to 600 g with a 100 g increment, and rough rice piled up to 350 g with a 50 g increment. For glass fragments and rough rice, three filling conditions including loose, free fall, and dense were tested to investigate the effects of porosity in a particle layer piled in a container (Fig. 3). For glass beads, the experiment was conducted only under the free fall condition because porosity in a particle layer did not change among three filling conditions.

In the loose condition, an acrylic resin net (lattice size 0.8 cm) was placed on the bottom of the resonator, and the net was pulled up after a sample was filled. This operation increased porosity among particles. The sample was discharged after each measurement. In the free

Fig. 3. Filling conditions of samples

fall condition, the sample was funneled into a container at the height of 10 cm. In the dense condition, the container was shaken at 170 rpm for 3 minutes with a shaker (Shaker SA31, Yamato) when the sample was filled. The surface of sample piled in the container was leveled at each measurement. The volume of the sample piled in the container was estimated by Eq. (1) using measured resonance frequency. Furthermore, the porosity in the particle layer was calculated by the relationship between particle density and bulk density.

RESULTS AND DISCUSSION

Figure 4 shows the frequency responses of the electrical impedance of the voice coil. The resonant frequency increased as the volume of water or particle layers in the resonator increased. The value of voice coil impedance lowered along an increase in the resonant frequency. However, a small value of voice coil impedance was observed when 50 g of rough rice was filled. This result implies that the experiment involved some

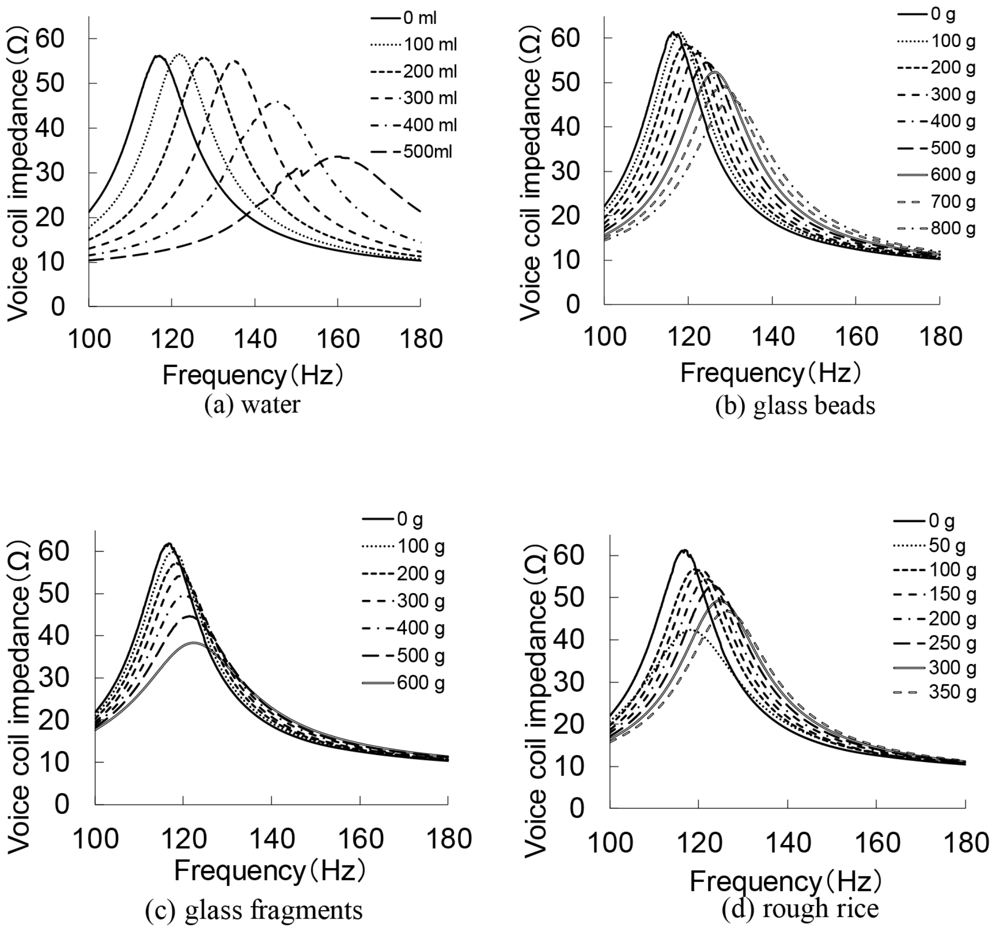

Fig. 4. Frequency responses of the electrical impedance of the voice coil.

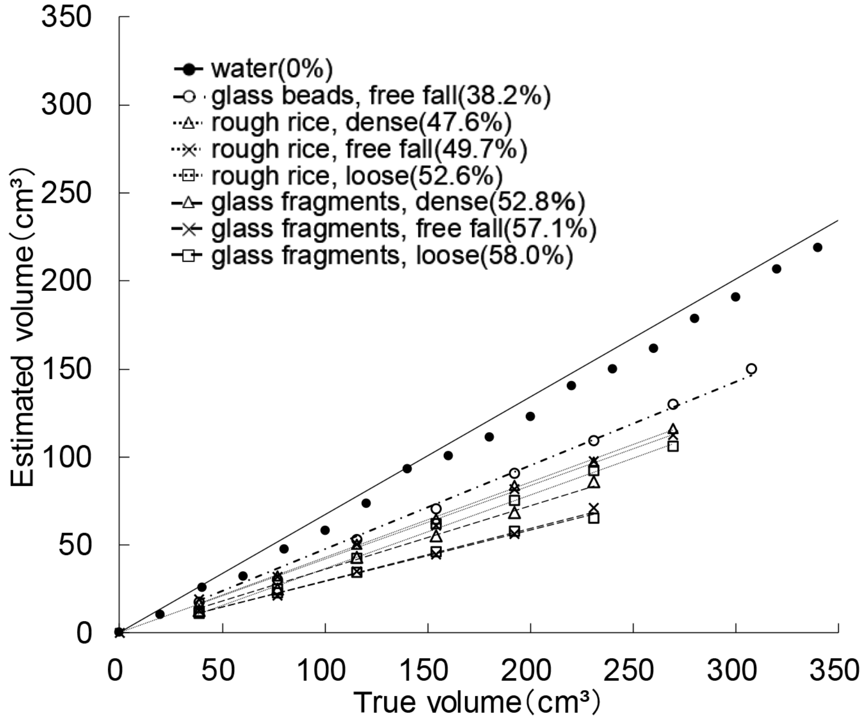

Fig. 5. Relationships between true volume and estimated volume.

measurement error.

Estimated volume had a strong linear correlation (r>0.99) with true volume for all the filling conditions and materials (Fig. 5). On the other hand, the volume was underestimated for water and all particle types as well as all the filling conditions. The reason for the underestimation was because the equation of volume estimation for an open–type resonator, Eq. (1), was applied to a closed–type resonator. In addition, we did not insert a partition plate between the loudspeaker and the resonator in this study as Nishizu *et al.* (2005b) did in a closed–type resonator. This probably decreased a spring constant of the upper cavity, resulting in reduced resonance frequency. We also estimated volume using the equation for a closed–type resonator (Nishizu *et al.*, 2005b). However, the volume was overestimated for a small range of volume, while it was underestimated for a large range of volume.

The extent of the underestimation increased linearly with an increase in porosity (%) in a particle layer: water (0%), beads under free fall (38.2%), rough rice under dense (47.6%), rough rice under free fall (49.7%), rough rice under loose (52.6%), glass fragments under dense (52.8%), glass fragments under free fall (57.1%), and glass fragments under loose (58.0%). A possible reason for underestimating volume was that vibration energy attenuated by porosity in a particle layer decreased resonant frequency. This result indicated that rough rice layer piled in a container can be estimated using Helmholtz resonance by clarifying the relationship between porosity among particles and the extent of volume underestimation. In addition, the effect of porosity needs to be considered in the equation of volume estimation.

CONCLUSIONS

The objectives of this study were to clarify the effects of particle types and porosity in a particle layer on the volume measurement and to investigate whether true volume of a rough rice layer piled in a container can be estimated using Helmholtz resonance. The following conclusions were drawn:

1. Estimated volume had a strong linear correlation (r>0.99) with true volume for all the filling conditions and materials.
2. As the porosity of the particle layer increased, the extent of underestimation of the volume increased. The effect of particle types on volume estimation was not confirmed.
3. Rough rice layer piled in a container can be estimated using Helmholtz resonance by clarifying the relationship between porosity among particles and the extent of volume underestimation.

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AUTHOR CONTRIBUTIONS

S. Inoue conducted experiments, analyzed the data, and wrote the paper. Y. Hirai designed the study, analyzed the data, and wrote the paper. S. Inagaki designed part of experimental procedures. E. Inoue, T. Okayasu, and M. Mitsuoka offered advices on the experiments and data analysis. All authors assisted in editing of the manuscript and approved the final version.

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