Evaluation of measurement accuracy of piezoelectric particle sizer using resonance flexural vibration modes of circular disc

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Abstract: Sand and small stones moving on the riverbed cause topographical changes such as local lowering and scouring. The measurement of particle size distribution of bed load is important to prevent river disasters, and a robust and simple particle sizer without using an electric power supply is required. In this study, a passive piezoelectric sensor for the measurement of the particle size distribution was developed and the continuous measurement for sequential impacts was analyzed. The sensor consists of an aluminum circular disc and an annular piezoelectric transducer. Naturally shaped gravel was employed as the bed load. When the gravel hits the surface of the sensor plate, resonance flexural vibration modes were excited on the sensor and electric power was generated through the piezoelectric effect. The size-discrimination parameters were defined by the spectral amplitudes of the resonance modes. The output signals of the sensor overlapped owing to the sequential impacts and the particle size distributions were estimated by time–frequency analysis.

Keywords: Bed load, Particle sizer, Piezoelectric sensor, Flexural vibration mode

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1. INTRODUCTION

Topographic changes in rivers caused by sediment particles on the riverbed increase the risks of river disasters [1]. The main sediment particles on the riverbed, bed load, are several millimeters in diameter [2,3], and the transport of bed load by river flow induces local scouring and unexpected retention around river structures such as bridge piers, thereby reducing the safety of river environments [4]. It is important to measure the amount and size distribution of bed load to prevent river disasters [5–7], and manual periodic direct sampling using screens is widely implemented [8,9]. However, the measurement accuracy depends on the size of each screen, implying that this method cannot precisely estimate the amount of bed load. In addition, direct sampling is time-consuming, expensive, dangerous for field workers especially during a flood [10,11], and unsuitable for real-time monitoring. The seabed can be investigated by ultrasonic measurement; conventional pulse-echo techniques enable the measurement of the configuration and particle distribution of the seabed by time–frequency domain analysis [12,13]. The pulse-echo method is useful for measuring the particle size distribution since the frequency characteristics of sound velocity and attenuation depend on the size and amount of particles [14–17]. Optical measurements using a laser have also been reported [18,19], although the measurement accuracy and measurable range depend on the transparency of the fluid used. Considering the practical use of wireless sensor networks in riverbeds in the future, the sensors in such networks should have a simple and robust structure and piezoelectric energy harvesting techniques can be utilized for the power supply [20–23].

Our group has developed an indirect measurement method to determine the size distribution of small particles using ultrasound piezoelectric sensors [24]. Each sensor consisted of a circular plate and a piezoelectric ring, and the collision of particles with the piezoelectric sensor induces a flexural vibration of the sensor surface plate, resulting in the generation of an electric voltage output induced by the piezoelectric effect. The frequency components of the output signal depend on the particle size,
enabling particle size discrimination by the Fourier transform of the output waveform; higher harmonic components of the signal were generated by the impacts of small particles. In our previous study [24], the sensor performance was evaluated using mm-sized perfect aluminum spheres, and the sequential impacts of particles were partially demonstrated. However, considering the practical use of the sensor in the riverbed as the next step, the accuracy of particle distribution measurement should be evaluated quantitatively using naturally shaped gravel where the sequential impacts inducing the output signals overlapped with each other. In this study, the measurement of sequential particle impacts was investigated using an ultrasound piezoelectric sensor to establish a real-time monitoring system for bed loads, and the particle distribution was quantitatively evaluated.

2. METHODS

We used a passive piezoelectric sensor with the same design as that employed in our previous study [24]. Figure 1 shows the configuration of the sensor consisting of an aluminum disc (diameter, 100 mm; thickness, 2 mm) and an annular piezoelectric lead zirconate titanate (PZT) ultrasound transducer (inner diameter, 20 mm; outer diameter, 30 mm; thickness, 2 mm; C-203, Fuji Ceramics, Japan) polarized in the thickness direction. The PZT ring was attached to the circular plate using epoxy resin. An aluminum cylinder (inner diameter, 60 mm; outer diameter, 100 mm) supported the edge of the circular plate so that the circular plate can vibrate in resonance flexural modes (the outer edge of the plate corresponds to the vibrational nodal circle). Considering the robustness for practical use in riverbeds in the future work, the sensor has no mechanical moving parts. The vibrational characteristics of the sensor were calculated by the finite element method (FEM) using commercial FEM software (ANSYS, Inc., Canonsburg, PA, USA); this calculation was performed to maximize the output voltage of the sensor and determine the configurations of the plate and PZT element while considering the sensing area and robustness in riverbeds. When particles hit the sensor surface, a flexural vibration was excited, and an electric signal was generated through the piezoelectric effect.

In our previous study, the measurement of particle size was carried out using aluminum spheres [24]. Considering the practical use in riverbeds, irregularly shaped bed loads were made to collide with the sensor sequentially. Crushed stones (Syowa-bussan, Japan) were employed to simulate bed loads, and their sequential impacts were measured using a large number of stones. The size distribution of the stones was measured directly under a microscope, and the stone size was defined as \( \phi = \frac{D_{\text{max}} + D_{\text{min}}}{2} \) (maximum diameter; \( D_{\text{max}} \), minimum diameter) since the crushed stones were not spherical. For the evaluation of the sensor as a particle sizer, the crushed stones were classified into three groups according to their size using sieves (group 1, \( 1 < \phi < 3 \) mm; group 2, \( 3 < \phi < 7 \) mm; group 3, \( 7 < \phi < 15 \) mm). The sizes for 500 samples were measured in each group (Fig. 2). Stones smaller than the mesh size of the sieve were included in each group because the stones were not spherical.

Figure 3 shows the experimental setup for the measurement of particle size. The crushed stones free-fell through a funnel at a height of 150 mm from the sensor surface and through a straight pipe such that as many stones as possible hit around the center of the sensor within a measurement time of 1.8 s. The sensor was inclined at 30° to prevent multicollisions of a stone and allow the sequential impacts of stones (the drop height and angle were previously found to have little effect on the measurement results [24]). The electric output signal of the piezoelectric sensor generated by collisions was observed with a digital oscilloscope at a sampling frequency of 500 kHz and the frequency spectrum was calculated by the Fourier transform. Considering the practical use of the sensor, the experiments should ideally be conducted in water. However, all of the experiments in this study were performed in air because it was difficult to control the impact position on the sensor surface and the impact velocity of stones by free fall in water.

3. SINGLE IMPACT

The frequency characteristics of the flexural vibration on the sensor surface were calculated by FEM. A continuous harmonic forced vibration with an amplitude of 1 N was applied in the vertical direction at the center of the circular plate in the simulation. Figure 4 shows the
frequency characteristics of the displacement amplitude in the vertical direction at the center of the sensor, and there were several resonance frequencies of the axisymmetric flexural vibration of the aluminum disc under 50 kHz: 5.24, 21.7, and 43.6 kHz (the vibration modes including those of the aluminum cylinder were generated at both 19.5 and 33.8 kHz). A prototype of the sensor was fabricated, and the frequency characteristics of electrical admittance were measured using an impedance analyzer (Fig. 5(a)). The resonance frequencies of the sensor were 4.52, 17.4, and 36.3 kHz, which were close to the values predicted by FEM (the resonance vibration at 26 kHz corresponded to that at 33.8 kHz in Fig. 4, and the resonance peak at 19.5 kHz in Fig. 4 did not appear in the prototype). The difference between the experimental and FEM results may be attributed to the material properties of the aluminum disc and PZT transducer used in FEM, and the fixing condition of the disc to the cylinder. In this study, we focused on the three axisymmetric resonance frequencies of the aluminum disc, 4.52, 17.4, and 36.3 kHz, because the particles hit around the center of the sensor surface. The vibration

Fig. 2 (a) Photograph and (b) particle size distributions of crushed stones in groups 1 to 3 (total number \( n = 500 \) in each group).

Fig. 3 Experimental setup for measurement of particle size.

Fig. 4 Frequency characteristics of displacement amplitude at the center of sensor surface calculated by FEM.
distributions on the sensor surface were measured at each resonance frequency using a laser Doppler vibrometer (LDV; NLV-2500, Polytec, Waldbronn, Germany) (Figs. 5(b)–5(d)). The axisymmetric flexural vibration mode was generated at each resonance frequency and a large number of concentric nodal circles appeared at higher resonance modes. In this study, we used these flexural resonance modes to estimate the particle size.

In our previous work [24], we found that the output waveform depended on the size of the particle that collided with the sensor surface. Figure 6 shows two representative output voltage waveforms from the sensor generated by a single impact of crushed stones. In the case of collision with a large stone, a periodic damped signal was generated, as shown in Fig. 6(a), whereas a collision with a small stone generated a periodic signal that included several frequencies (Fig. 6(b)). Figure 7 shows spectrograms of the output waveforms in Fig. 6 calculated by short-time Fourier transform. Considering the peak detection of the resonance frequencies and the overlaps of the signals in the case of sequential impacts (described later), the Hann window with a frame width of 2.0 ms was used. In the case of collision with a smaller stone, three main spectra appeared clearly (Fig. 7(b)), corresponding to the resonance frequencies of the flexural vibration modes of the sensor at 4.52, 17.4, and 36.3 kHz shown in Fig. 5. Figure 8 shows the time variation of the amplitudes of these three resonance spectra. The horizontal axis indicates the central time of the frame width for the short-time Fourier transform. The spectral amplitudes reached a peak simultaneously with the collision with a stone and then decayed exponentially. Here, we determine the dimensionless amplitude ratios of these spectra, \( R_1 = A/(B + C) \) and \( R_2 = B/C \), to predict the size of stones, where \( A, B, \) and \( C \) indicate the peak spectral amplitudes at the resonance frequencies of 4.52, 17.4, and 36.3 kHz, respectively, because the size of stones largely affected the frequency components of the output signal rather than the signal amplitude [24]. This finding implies that the frequency components of the output signal depend mainly on the contact area between the stones and the sensor surface; the generation of higher-frequency components requires pinpoint contacts between them. The use of the dimensionless \( R_1 \) and \( R_2 \) means that the prediction of particle size does not depend on the amplitude of the pulsed signal. In the cases in Figs. 8(a) and 8(b), \( R_1 \) was calculated to be 8.74 and 2.95 (\( R_2 \) values were 3.46 and 1.95), respectively; the collision with smaller stones gives smaller \( R_1 \) and \( R_2 \) values since larger \( B \) and \( C \) values are generated at higher resonance frequencies. Assuming the spectrum amplitudes decay exponentially and the time variation can be expressed as \( v(t) = V_0 \exp(-t/\tau) \) (\( V_0 \) is the peak value) in

\[ \text{Fig. 5} \quad \text{(a) Frequency characteristics of electric admittance of sensor and vibrational distributions on sensor surface at resonance frequencies of (b) 4.52, (c) 17.4, and (d) 36.3 kHz.} \]
Fig. 8(b), the time constant \( \tau \) was calculated to be 16, 5.9, and 2.6 ms for 4.52, 17.4, and 36.3 kHz, respectively; the time constant decreased as the resonance frequency increased.

The finding that the amplitude ratios depend on the particle size means that the behavior of crushed stone at the moment of collision affects the measurement accuracy. Repeated experiments were conducted using one stone (mass, 0.14 g; minimum diameter, 2.6 mm; maximum diameter, 9.9 mm), and the moments of collision were observed by recording with a high-speed camera. We categorized the collisions into “point collision (Fig. 9(a))” or “plane collision (Fig. 9(b))” on the basis of the behavior of stones observed on the obtained images. Figure 10 shows the \( R_1 \) and \( R_2 \) values for the point and plane collisions. The plots and error bars indicate the average values and the standard deviations for 10 trials. For comparison, the result for an alumina sphere (mass, 0.14 g; diameter, 4 mm) is also shown. The standard deviations of the amplitude ratios increased in the order of alumina
sphere, point collision, and plane collision, indicating that the contact area between the stones and the sensor surface is an important factor for the measurement accuracy. The same tendency was observed in our previous work using alumina spheres of different sizes [24]. The finding that the standard deviation increased with the contact area is attributed mainly to the repeatability of the impact position on the sensor surface. Strictly, the impact positions were distributed around the center of the sensor surface and the amplitude ratio changed slightly, although the stones were controlled to hit the center of the sensor surface, as shown in Fig. 3. This amplitude ratio variation depends on the relationship between the wavelength of each resonance flexural vibration mode and the distance between the center and the impact position; in the case of a higher resonance mode with a shorter wavelength, the impact position should be controlled precisely. In addition, the behavior in plane collision induced a larger output signal variation than the other two cases because the contact area of naturally shaped stones and the sensor surface varied widely.

4. SEQUENTIAL IMPACTS

The sequential impacts were investigated by controlling the crushed stones to hit around the center of the sensor surface sequentially, and the output signal was observed for 1.8 s. The typical output signal of the sensor generated by the sequential impacts is shown in Fig. 11(a). The sequential impulse signals appeared upon collisions, and some of the signals overlapped in the time domain. As in the analysis of a single impact, the spectrogram of the output signal was calculated by short-time Fourier transform with a frame width of 2 ms. Figure 11(b) shows the change in the spectral amplitude of each of the resonance frequencies at 4.52, 17.4, and 36.3 kHz with respect to time from 0 to 0.2 s in Fig. 11(a). The horizontal axis indicates the central time of the frame width for short-time Fourier transform. The spectral amplitude of each resonance frequency reached the peak immediately after the collisions with the crushed stones similarly to the single impact. The peak spectral amplitudes of the fundamental mode $A$ (4.52 kHz) were larger than those of the higher-order modes $B$ and $C$ (17.4 and 36.3 kHz), although the sequential pulsed signals overlapped and the time resolution of the fundamental mode was lower owing to the larger time constant as described above. On the other hand,
in the case of the higher-order modes, shorter time constants than that of the fundamental mode resulted in a larger number of rising points of inflection in the time domain and enabled the prevention of the overlaps of sequential pulsed signals, although the peak values at each inflection point were small and the signal-to-noise (SN) ratio decreased. This finding means that there is a tradeoff between the SN ratio and the overlaps of the sequential signals, and in this study, two size-discrimination parameters \( R_1 = A / (B + C) \) and \( R_2 = B / C \) were compared. The numbers of rising points of inflection at 4.52 and 17.4 kHz were counted as the numbers of collisions with crushed stones for \( R_1 \) and \( R_2 \), respectively; 202, 254, and 183 (or 245, 270, and 165) collisions were counted for \( R_1 \) (or \( R_2 \)) in groups 1, 2, and 3, respectively. The \( R_1 \) and \( R_2 \) values for each collision were calculated from each spectral amplitude to estimate the size of crushed stones. Figure 12 shows the histograms of \( R_1 \) and \( R_2 \) for each group. It was confirmed that these amplitude ratios tended to increase with the particle size (in the order of groups 1, 2, and 3) similarly to the single impact.

Here, the size distribution of crushed stones was estimated experimentally from the distributions of \( R_1 \) and \( R_2 \), although the theoretical model should be investigated. The relationships between the particle size and \( R_1 \) and \( R_2 \) are shown in Fig. 13. The plots and error bars in the horizontal axis indicate the average standard deviation of the size distribution of crushed stones in each group.
measured directly under an optical microscope (Fig. 2), and those in the vertical axis indicate the average standard deviations of \( R_1 \) and \( R_2 \) measured for the sequential impacts (Fig. 12). \( R_1 \) and \( R_2 \) increased with the particle size, and the linear regressions \( R_1 = 0.53\phi + 2.48 \) and \( R_2 = 1.9\phi - 0.84 \) [\( \phi \) is the particle size (mm)] could be determined, enabling the transformation of the histogram of the amplitude ratio (Fig. 12) to the particle size distribution, although the coefficients of variation (= standard deviation/average value) for the amplitude ratios increased with the particle size (considering the residual sum of squares, linear regression was used, although exponential regression was used in our previous work [24]). Figure 14 shows the particle size distribution measured directly under a microscope and that estimated from \( R_1 \) and \( R_2 \) in each group. The particle size distribution estimated using the sensor showed the same tendency as in the true values measured under a microscope; the distribution shifted to larger sizes in the order of groups 1 to 3, and the values estimated from \( R_2 \) (Est. \( (R_2) \)) showed better agreement with the true values (Meas.) than those estimated from \( R_1 \) (Est. \( (R_1) \)). The results are summarized in Table 1. Note that the difference in standard deviation, not the average values, between the true and estimated values is important for the evaluation of measurement accuracy because the estimated distributions were calculated by linear transformation using each average value (Fig. 13) and the average values should correspond to each other. The difference between the estimated and true values may be attributed to several factors. First, the impact position on the sensor surface affects \( R_1 \) and \( R_2 \) (strictly, the crushed stones collided “around” the center of the sensor). The amplitudes of the harmonic components largely depend on the impact position; it would be difficult to excite the resonance mode if the impact point corresponds to the vibrational nodal points [24]. In addition, the variation in contact area between the naturally shaped stones and the sensor surface reduced the measurement accuracy, as shown in Fig. 10. The collision intervals of stones would also largely affect. We will investigate in our future research the theoretical model to predict the particle size distribution.

5. CONCLUSIONS

The continuous measurement of the particle size distribution using a piezoelectric particle sizer was discussed. The sensor prototype used has a simple structure and is robust owing to the absence of mechanical moving parts. The resonance flexural vibration was excited on the sensor surface upon collisions with crushed stones, and the electric output signal was generated through the piezoelectric effect. The ratio of the frequency components was defined as the discrimination parameter so that the particle size distribution can be estimated from the output signal, and larger harmonic components were generated upon collisions with smaller stones. The particle size

![Fig. 14 Histograms of particle sizes measured under a microscope (Meas.) and estimated from \( R_1 \) (Est. \( (R_1) \)) and \( R_2 \) (Est. \( (R_2) \)) for groups 1, 2, and 3.](image)

![Table 1 Average values and standard deviations of particle distributions in groups 1, 2, and 3 measured under a microscope and estimated from \( R_1 \) and \( R_2 \).](table)
distribution estimated using the sensor showed good agreement with the true value measured under a microscope. Experiments in water should be conducted as the next step, and the measurement system with flowing water is required to obtain a large SN ratio in water. If an equivalent measurement accuracy can be obtained in water, particle size discrimination on riverbeds will be achieved and this technique will undoubtedly improve a real-time monitoring system for bed loads.

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