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Piezoelectric particle sizer for measuring bed load using a combination of resonance vibration modes

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ABSTRACT

To predict environmental changes and prevent disasters in rivers it is important to track how the size distributions of sand and stones in the riverbed change over time. In this paper, we used a passive piezoelectric sensor to measure the particle distribution of a simulated bed load. The sensor had a simple, robust structure consisting of a circular aluminum plate and an annular piezoelectric transducer. The detection characteristics were evaluated by measuring the impact of alumina spheres with diameters of 3–8 mm in air. When particles hit the sensor, the impact excited a flexural vibration in the circular plate, generating electric power through the piezoelectric effect. The electric output signal exhibited two main frequency peaks, at 16.3 and 66.7 kHz, whose amplitude ratio depended on particle size. These two frequencies correspond to the fundamental and third resonance vibration modes. When particles hit the sensor surface sequentially, we could determine their particle sizes from short-term frequency analysis of the observed voltage waveform.

1. Introduction

The bed load of a riverbed is defined as all moving sediment particles with a size of several millimeters [1–3]. Moderate- and long-term flow of the bed load changes the topography of the riverbed through means such as scouring and lowering [4], which damages the river's structure [5]. To prevent river disasters, it is important to track how the amount and size distributions of sand and stones in the riverbed change over time [6–8]. Although periodic direct sampling—measuring the particle size distribution of the bed load by hand using screens—is widely used [9,10], its measurement accuracy, which depends on the size of the screens, is low, and this method cannot precisely estimate the amount of bed load. In addition, using direct sampling often is time-consuming, expensive, and dangerous, especially during floods [11,12].

Seabeds can also be investigated using ultrasonic measurements; specifically, the classical ultrasonic pulse-echo technique can measure the configuration and particle distribution of a seabed [13,14] because the reflected pulsed echo includes various information in both the time and frequency domains. The pulse-echo method is useful for measuring the particle distribution because the ultrasound velocity, attenuation and the frequency spectrum of the ultrasound pulse depend on the amount and size distribution of the particles [15–17]. Although optical measurement techniques using a laser sheet [18,19] are also promising, several factors, such as turbidity, affect their accuracy.

In the present study, we seek to develop a precise, real-time technique for measuring a bed load with a particle size of several millimeters. To be practical in rivers, the measurement system should be simple, robust, cheap, and batteryless (or consume little power) [20–22]. Acoustic emission method using piezoelectric sensors is a promising candidate to solve this problem. Hancke et al. [23] and Uher et al. [24] investigated the acoustic emission generated by collision of micro-meter-sized particles and the effect of the size distribution on the resonant structure and performed the modal analysis to determine the particle size distribution. Gao et al. also modelled the relationship between the resulting impact signals and particle size mathematically, allowing particle size distribution to be inferred [25,26]. We propose a method for measuring the particle distribution of the bed load, using a passive piezoelectric transducer and resonance vibration modes, and report its detection characteristics in air. By analyzing the sensor's electric output waveform, generated by impacts with particles, we measured the particle size of a simulated bed load with millimeter-size particles.

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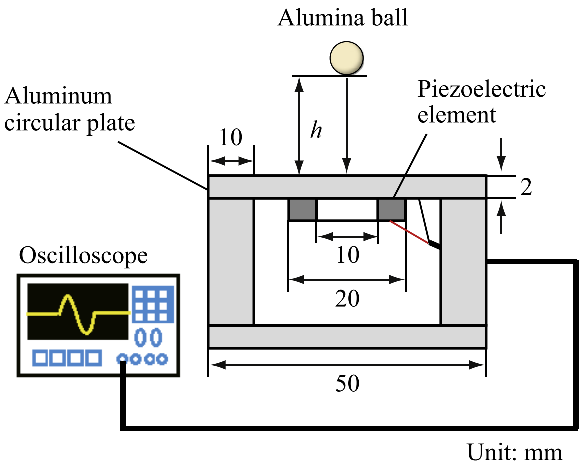

Fig. 1. Configuration of the piezoelectric passive sensor and the experimental setup.

2. Configuration of the piezoelectric transducer

Fig. 1 shows the configuration of the piezoelectric transducer. The transducer has a simple structure and can be embedded in the base of piers in rivers; it consists of a circular aluminum plate (diameter: 50 mm; thickness: 2 mm) and an annular piezoelectric element (inner diameter: 10 mm; outer diameter: 20 mm; thickness: 2 mm; C-203, Fuji Ceramics, Fujinomiya, Japan) made from lead zirconate titanate (PZT) and polarized in the thickness direction. The PZT transducer was attached to the circular plate using epoxy. An aluminum cylinder (inner diameter: 30 mm; outer diameter: 50 mm) supported the edge of the circular plate so that the circular plate vibrated in the resonance flexural modes. The opposite side of the vibrating plate was sealed with an aluminum plate, and the air-backed transducer can be used in water. The designs of the plate and PZT element were determined by using finite element analysis (FEA) in commercial FEA software (ANSYS, Inc., Canonsburg, PA, USA), considering the sensing area and the sensor's robustness in a river. A continuous forced harmonic vibration in the vertical direction (*z* direction) was applied at the center of the circular plate with an amplitude of 1 N as the boundary condition, and the vibration amplitude and the output voltage were calculated. To efficiently generate the flexural vibration modes on the circular plate and obtain the larger output voltage from the PZT element, we optimized the configurations of the aluminum circular plate and the PZT ring. The hard piezoelectric material C-203 with a high quality factor is suitable to obtain large output voltage since the sensor utilizes the resonance vibration modes. The detection characteristics of the prototype were evaluated in air. The simulated bed load was composed of alumina spheres with several diameters (*&x3D5;* = 3, 5, and 8 mm), allowed to free-fall from several drop heights (h = 100–300 mm). The flexural vibrations were generated on the plate by collisions with the spherical particles, and the electrical output signal of the PZT transducer was measured by a digital oscilloscope (DPO3014, Tektronix, Tokyo, Japan) through the piezoelectric effect. All of the experiments in this paper were performed in air.

3. Particle size determination by frequency analysis

Fig. 2 shows a representative output voltage waveform from the sensor, generated by a single impact with an alumina particle. This impact generated a damped oscillational signal with a time constant of ~1.7 ms. Fig. 3 shows enlarged views of the waveforms at the moment of impact with spherical particles of all three diameters dropped from h = 200 mm. The particles vertically collided with the center of the sensor surface. The waveforms were normalized by each maximum value for comparison, although the voltage amplitude increased with particle size at a fixed drop height h. Unfortunately, because the maximum value of the voltage signal also depends on the kinetic energy of the particle before the impact, the particle size cannot be determined from only the voltage amplitude. Periodic vibrational signals appeared whose waveform depended on particle size. Fig. 4 shows the frequency spectra of the waveforms in Fig. 3 calculated by Fourier transformation and normalized by each maximum value. Two main frequency components, at 16.3 and 66.7 kHz, appeared in all cases.

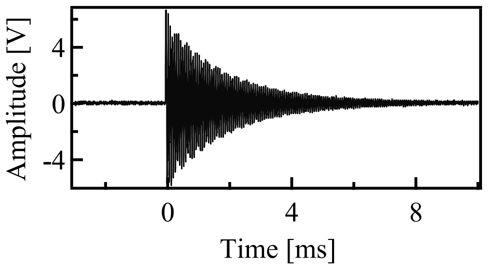

Fig. 2. Typical output voltage waveform of the piezoelectric sensor. The damped oscillation signal was generated by the impact of an alumina sphere.

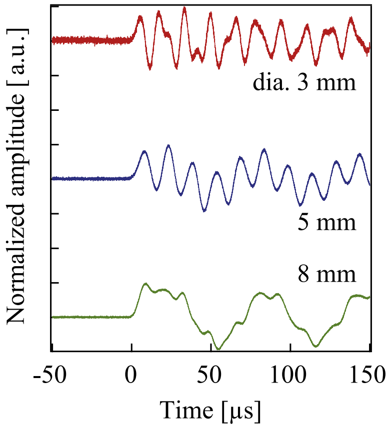

Fig. 3. Output voltage waveforms of the piezoelectric sensor for several sphere diameters.

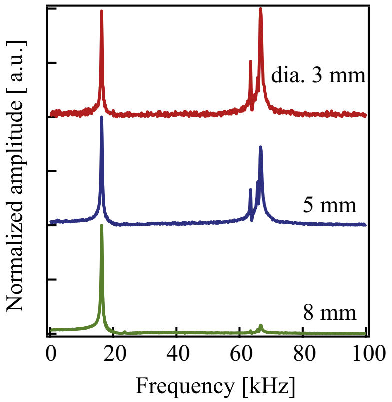

Fig. 4. Frequency spectra of output voltages for particles with various diameters.

To investigate these two frequencies, we measured the out-of-plane vibration distribution on the circular plate by using a laser Doppler vibrometer (NLV-2500, PI, Polytec, Waldbronn, Germany), applying a continuous sinusoidal electrical signal at each frequency to the piezoelectric transducer (Fig. 5). The vibrational amplitudes were normalized by each maximum value, and the solid circles