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Ultrasonic inspection of sludge accumulated in plastic pipes using meta-slab mode-converting wedge transducers

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ABSTRACT

Noninvasive ultrasonic inspection of sludge accumulated inside fluid-flow pipes is important to avoid a catastrophic pipeline failure. Although an earlier ultrasonic inspection method is applicable to both metal and plastic pipes, it can be applied only when the height of the accumulated sludge inside a plastic pipe is larger than about 1/5 of the pipe diameter. Considering the wide use of plastic pipes in various industries, lowering the detectable height of the accumulated sludge can be critically important. Here, we propose a non-conventional method to inspect the sludge inside a plastic pipe, the height of which can be as low as zero in theory. While the earlier method used only L (longitudinal) waves for the inspection, the proposed method uses different wave modes in different media along the wave passage from a PZT transducer to the fluid via the pipe wall. Specifically, we generate an L wave from the PZT, fully mode-convert it to an S (shear) wave before transmitting it to the wall of a plastic pipe, and convert it back to an L wave in the fluid. The suggested wave passage should ensure that the L wave in the fluid propagates horizontally or parallel to the fluid surface for accurate height estimation. We show why using the S wave in the pipe wall is critical in lowering the detectable height of the sludge; additionally, for the full-power L-to-S mode-conversion from the PZT to the pipe wall, a meta-slab mode-converting wedge is designed by a PEEK-based metamaterial. The specific wedge configuration will be also presented. Using the proposed novel sludge inspection method, we performed numerical simulations and experiments in PVC pipes in which simulated sludges of different heights were considered. Our numerical and experimental results confirm that the detectable heights of the accumulated sludge were considerably lower than those by the existing approach that does not use the S wave.

1. Introduction

This study is interested in a non-invasive ultrasonic inspection of the severity of sludge accumulated in a flow flowing inside plastic pipes such as PVC (Polyvinyl chloride), PE (Polyethylene), or PP (Polypropylene) pipes. The present research focused on the development of a new ultrasonic method to detect accumulated sludge of a height that cannot be detected by any of the existing methods. Considering the necessity of inspecting sludge accumulation in many industries, such as the semiconductor industry, where particles included in a fluid flowing inside a pipe could be accumulated at a specific location, early detection of sludge accumulation over a certain height can avoid dangerous fluid leaks due to pipe blockage. Recently, an ultrasound-based inspection of sludge accumulation was reported for both metal and plastic pipes [1]. Specifically, the left illustration of Fig. 1(a) shows an installed pair of wedge transducers used to estimate the height of accumulated sludge inside a pipe (see Ref. [1]). If an ultrasonic wave generated by a transmitting transducer located at a specific height does not reach a receiving transducer located at the other side of the pipe at the same elevation, the sludge is declared to be accumulated over that height. In the case of sludge inspection in a metal pipe, the generated L (longitudinal) wave from a PZT element is transmitted through the plastic wedge to be mode-converted to an S (shear) wave, and the S wave is finally converted to an L wave which propagates horizontally inside a fluid. Due to the difference in the wave speed between the wedge, the pipe, and the water, the ultrasonic propagation path forms a convex path. The mode-conversion approach is critical in lowering the measurement height of the sludge, but Ref. [1] showed that it could not be used for

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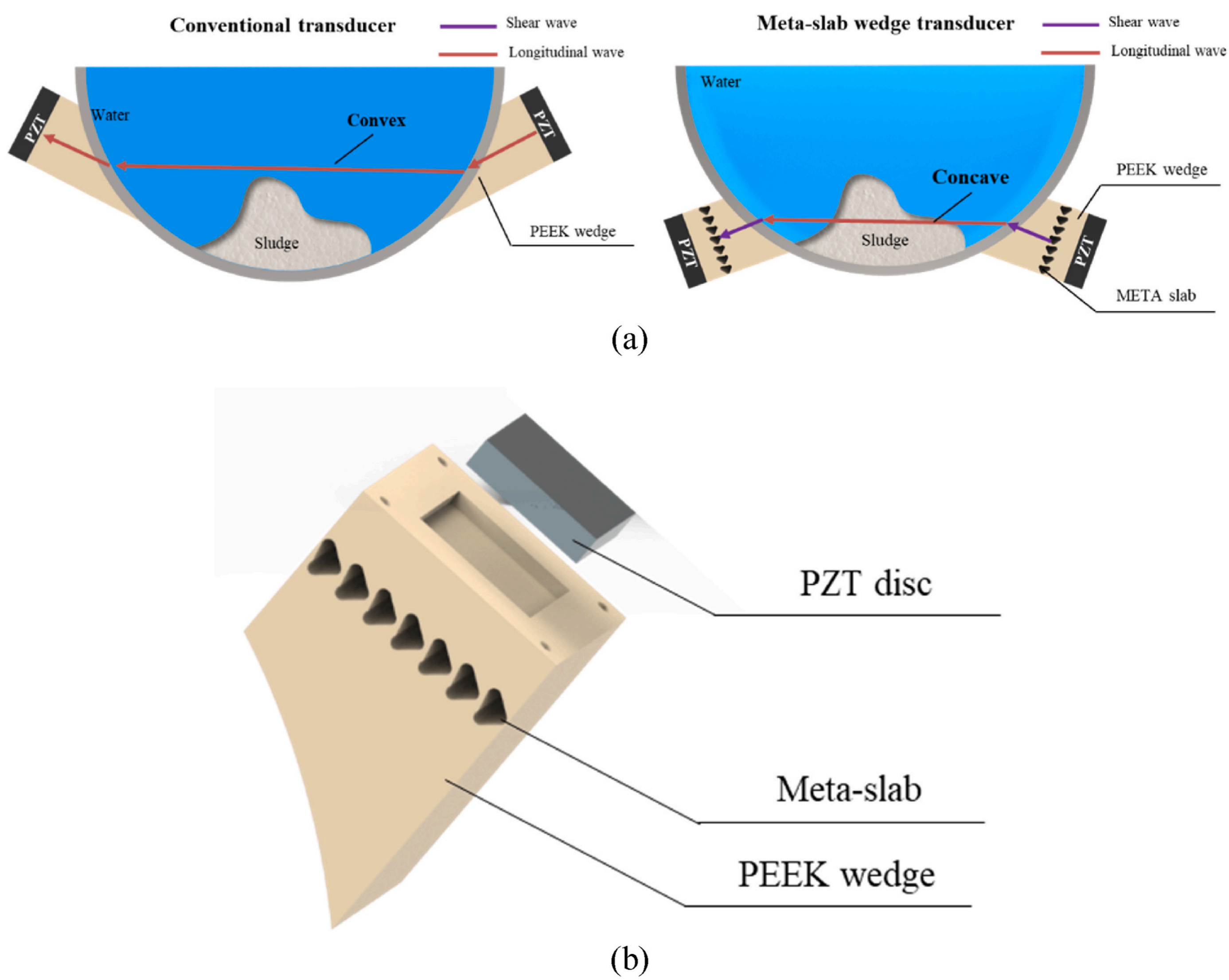


Fig. 1. Overview of non-invasive ultrasonic techniques for estimating the height of sludge accumulated in a plastic pipe. (a) Left: existing method (Ref. [28]) using a pair of conventional transducers; right: proposed method using a pair of meta-slab wedge transducers. In either case, the transducers are all installed circumferentially on the outer wall of a plastic pipe. (b) The detailed configurations of the meta-slab wedge transducer consist of a PZT disc and a PEEK wedge in which a fabricated mono-layer meta-slab is embedded. The dark regions in the meta-slab denote voids.

plastic pipes. In fact, sludge accumulated lower than a height of 0.19*D* cannot be detected by the method in Ref. [1]. Motivated by this observation, we developed a new method to ultrasonically detect sludge with a height smaller than 0.19*D* in plastic pipes.

At this point, it is worth examining why the inspected height of sludge is limited for the case of plastic pipes when the method developed in Ref. [1] is used. The main reason is that because the mechanical impedance PEEK composing the wedge is nearly the same as that of an inspected plastic pipe, mode-conversion cannot be used. Therefore, the refraction of the incident L wave inside a plastic pipe at a low angle is not possible. Therefore, the L mode is used through the whole wave passage from the transmitting transducer to the receiving transducer via a fluid inside a plastic pipe. As mentioned above, it was shown (Ref. [1]) that the ultrasonic detection method works only when the sludge is accumulated over 0.19*D*. Our approach, lowering the height of sludge detection presented here, is to develop a new non-conventional method using meta-slab mode-converting wedge transducers for sludge inspection in plastic pipes. If such transducers are used, the desirable mode-conversion phenomenon that is critical in lowering the detectable sludge height can be achieved. In theory, the inspectable sludge height by the proposed method in this study can be virtually zero.

Because ultrasonic-based inspection methods for various flow-related applications were carefully reviewed in Ref. [1], we will not repeat them in detail but will briefly review the underlying related research. As for pipe-related inspection ultrasonic methods, there are transit-time ultrasonic flowmeters [2–4] used to measure the flow velocity of a fluid inside a pipe and guided-wave methods to detect cracks in pipes [5–8]. In addition, more closely related studies on the detection of sludge accumulation in pipes are presented in Refs. [9–24]. However, these studies and a recent study by the authors [1] are not applicable to the non-invasive estimation of sludge accumulation in plastic pipes when the height of the accumulated sludge is lower than 0.19*D*.

The method we are newly proposing in this paper is described in the right illustration of Fig. 1(a). It shows a pair of ultrasonic *meta-slab*[1]

[1] The name "meta-slab" is an abbreviation for metamaterial slab. It is called a metamaterial slab because the effective material property of the slab exhibits a special anisotropy not attainable with natural materials. Thereby, some elaborately designed holes are drilled in the base material to achieve the desired anisotropic material property needed to achieve the desired wave phenomenon which is the full mode-conversion phenomenon in this case.

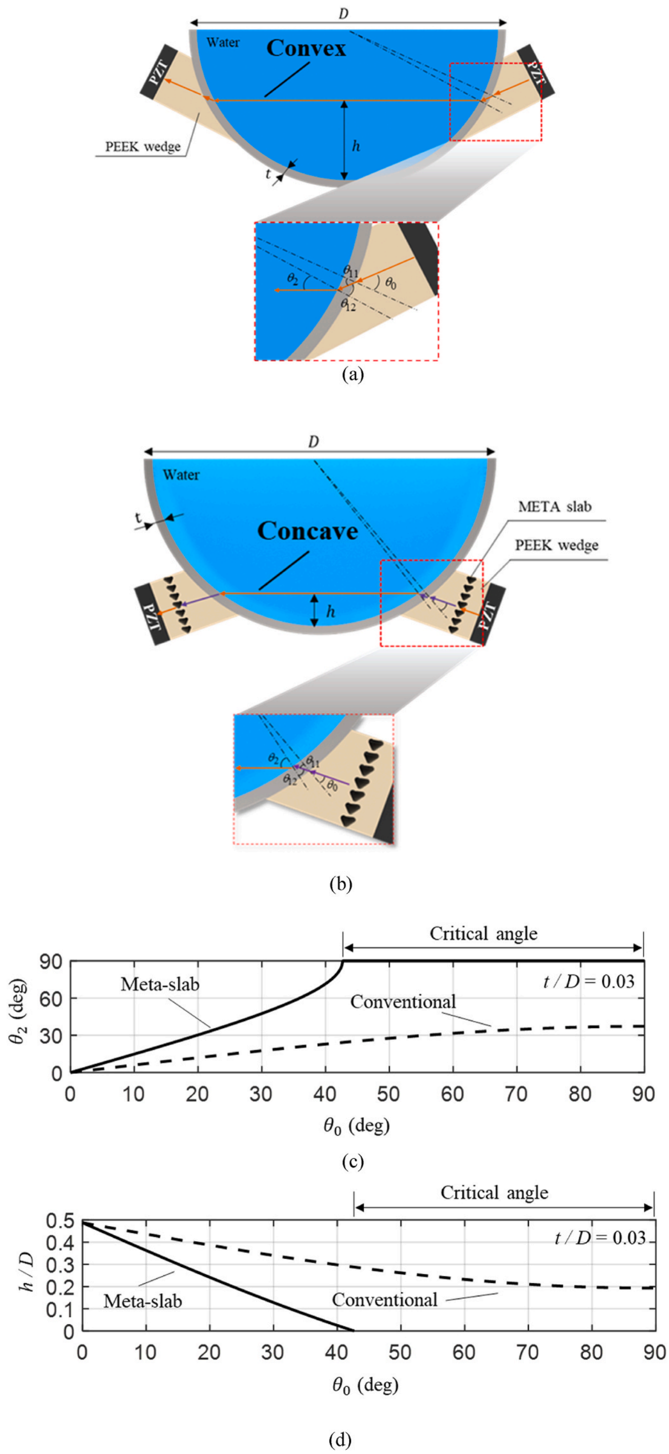


Fig. 2. Wave passage analysis for a fluid-filled PVC pipe in a non-invasive ultrasonic sludge accumulation inspection based on (a) a pair of conventional transducers using an L wave (in orange) only everywhere and (b) a pair of meta-wedge transducers using L (in orange) and S (in purple) waves depending on the wave passage location. The black regions in the region of the meta-slab denote voids machined into the base PEEK material. (c) The refracted angle θ_2 as a function of θ_0 and (d) the detectable height h of the accumulated sludge. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Mechanical properties of the PEEK and PVC.

Properties	Material		
	PEEK	PVC	Water
ρ: Density (kg/m^3)	1320	1380	1000
G: Shear modulus (Gpa)	1.51	1.55	–
E: Young's modulus (Gpa)	4.23	4.28	–
c_L: L wave speed (m/s)	2610	2400	1500
c_S: S wave speed (m/s)	1070	1060	–

wedge transducers installed circumferentially on the outer wall of a pipe below the water surface, and the passage of the ultrasonic waveforms a concave path. Fig. 1(b) shows the detailed configuration of the meta-slab wedge, which consists of the PZT unit, the mode-converting meta-slab embedded in the PEEK wedge, and the remaining PEEK wedge conforming to the curved surface of the pipe the inside of which is to be ultrasonically inspected. Once the PZT unit generates an L wave, it is fully (nearly by 100 % efficiency) converted to an S wave when it passes through the meta-slab of the PEEK wedge. Then, the converted S wave travels through the conforming wedge part and propagates into the pipe wall as the same S wave. Then, the S wave obliquely incident onto the pipe is finally mode-converted to an L wave in the fluid inside the pipe. The reason why the mode-converting slab is called a meta-slab is that it is made of an elastic metamaterial with an extremely effective anisotropy that cannot be found in nature. Achieving mode conversion using a meta-slab was first reported in Refs. [25,26] and later developed in Ref. [27]. The meta-slab was also applied in an ultrasonic flowmeter [28]. Here, the meta-slab used in our study was designed by extending the method given in Ref. [29]. As for manipulating more general mode conversion, Tian et al. [30,31] proposed a resonant elastic metamaterial for the mode conversion of the Lamb waves to the shear horizontal wave, and Lee et al. [32,33] proposed a non-resonant elastic metamaterial for the mode conversion between L and S waves at an arbitrary angle of incidence. On the other hand, this study will mainly utilize the mode conversion phenomenon between L and S waves at a normal incidence.

The next section presents the working principle of the height measurement of accumulated sludge and the design principle of the full-power L-to-S mode-converting meta-slab wedge. Then, we will present the simulation results to show how the proposed method works for sludges of different heights. Finally, the experimental results for PVC pipes will be presented followed by concluding remarks.

2. Working principle of the meta-slab mode-converting wedge transducer

To show why the proposed approach using meta-slab mode-converting wedge transducers can lower the measurement height of accumulated sludge in a plastic pipe compared with the existing method [1], we compared the working principle of the proposed method with that of the existing method. Fig. 2(a) and (b), respectively, show the wave passages used in the conventional and proposed sludge accumulation inspection methods.

In the conventional method depicted in Fig. 2(a), an L wave is generated by a PZT unit of the transmitter (shown on the right side), and it propagates through a plastic wedge made of PEEK. The L wave is then incident onto a PVC pipe at the wedge angle θ_0 as sketched in the zoomed view and is refracted into the pipe in the same L wave mode at the refraction angle. The refraction angle θ_{11} can be calculated from Snell's law as

$$\theta_{11} = \sin^{-1}\left(\frac{c_L^{PVC}}{c_L^{PEEK}}\sin(\theta_0)\right), \tag{1}$$

where c_L^{PVC} and c_L^{PEEK} denote the longitudinal wave speeds in the PEEK

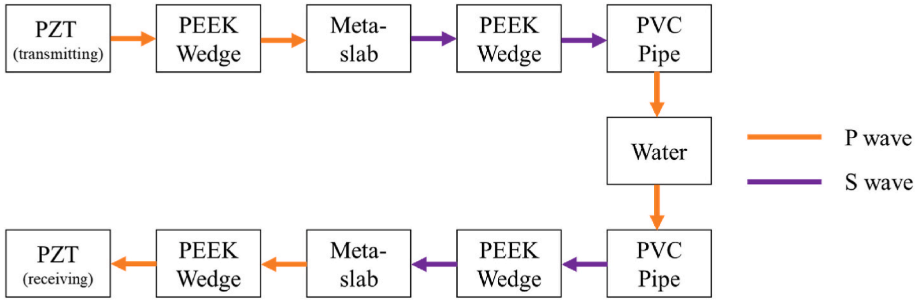


Fig. 3. Wave modes at different locations in the wave passage.

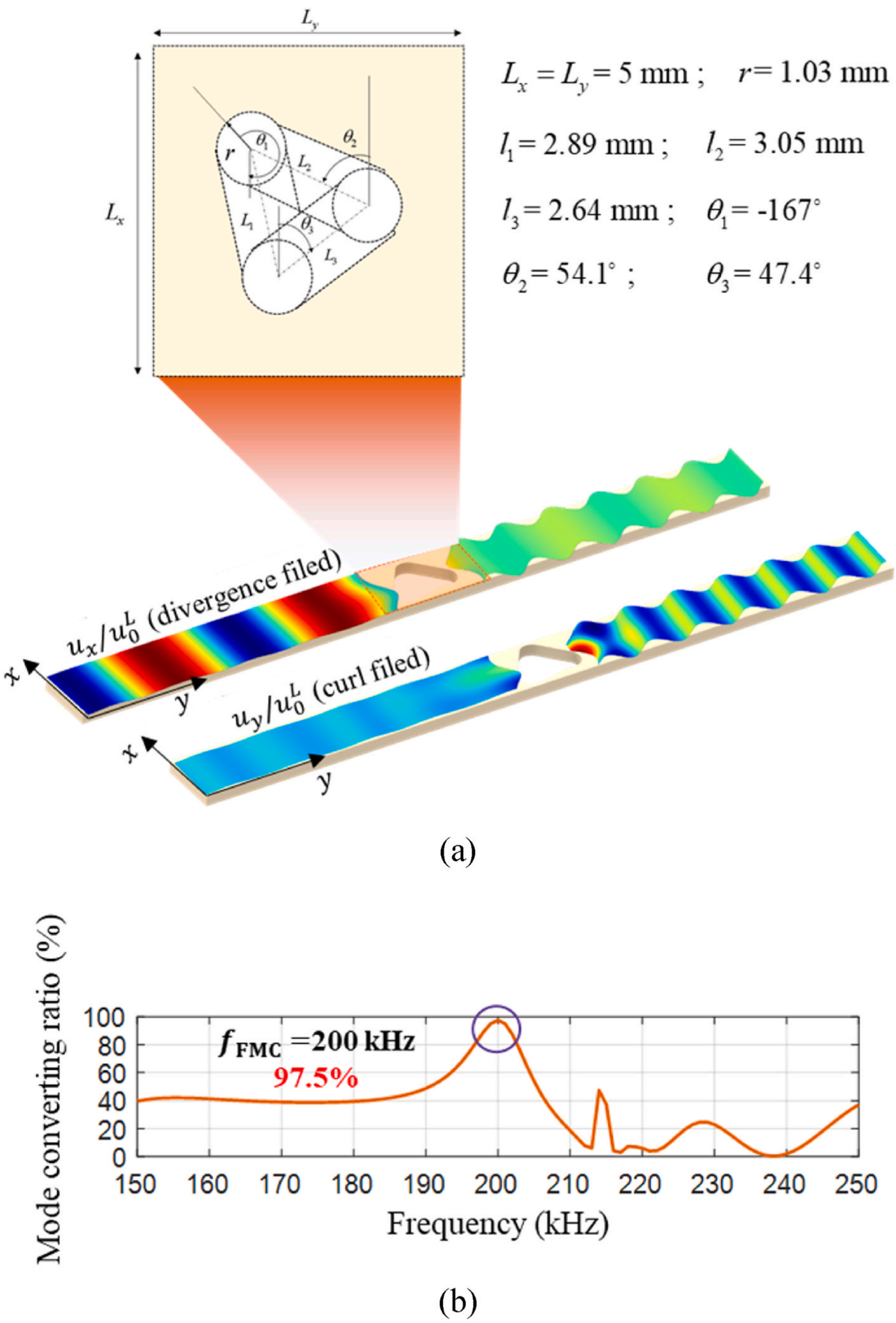


Fig. 4. Simulation results for the designed unit cell of the meta-slab at the target frequency of 200 kHz. (a) the L wave (divergence) and S wave (curl) displacement fields plotted on the deformed shape of the base medium (PEEK) and (b) the transmitted S wave to the incident L wave through the meta-slab as a function of the frequency.

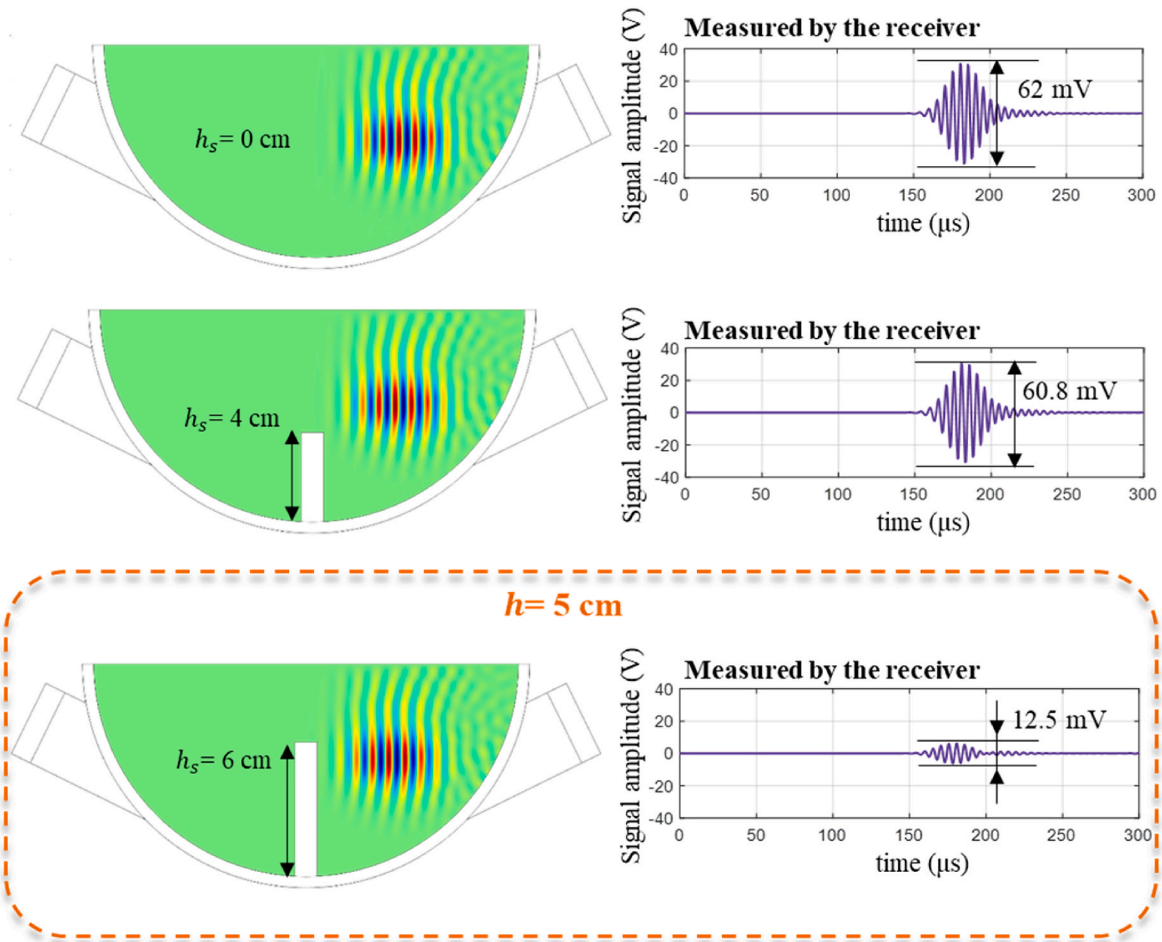


Fig. 5. The finite element simulation results for the convex path (using an L wave only) achieved by a conventional transducer (h_s: the height of a rigid block simulating accumulated sludge; h: the height of the horizontal propagation wave in the water).

and PVC. The material properties of the PEEK, PVC, and water are given in Table 1.

Considering the pipe thickness t, the refraction angle θ_{11} becomes the incident angle θ_{12} at the interface between the pipe and the fluid inside the pipe. The angle θ_{12} can be calculated as

$$\theta_{12} = \sin^{-1}\left(\frac{\frac{D}{2}}{\frac{D}{2}-t}\frac{c_L^{PVC}}{c_L^{PEEK}}\sin(\theta_0)\right), \tag{2}$$

where D is the diameter of the pipe. When the L wave enters the fluid, it is refracted to an L wave at the refraction angle θ_2 calculated by Snell's law as

$$\theta_2 = \sin^{-1}\left(\frac{\frac{D}{2}}{\frac{D}{2}-t}\frac{c_L^{Water}}{c_L^{PEEK}}\sin(\theta_0)\right), \tag{3}$$

where c_L^{Water} is the longitudinal wave speed in the fluid. As suggested in the figure, the propagation path in the water should be parallel to the water surface for the sludge height estimation. If PEEK wedges are installed at an angle to a pipe partially filled with a liquid, especially at a low level, ultrasonic waves cannot pass through the liquid, and the receiver cannot detect the signal. Therefore, the wedges must be placed symmetrically on both sides of the pipe. If the L wave in the water propagates horizontally, the height of the ultrasonic wave path h in the water from the bottom of the pipe can be calculated as

$$h = \frac{1}{2}\left(D - 2t - D\frac{c_L^{Water}}{c_L^{PEEK}}\sin(\theta_0)\right). \tag{4}$$

Fig. 2 (c) and (d), respectively, show θ_2 and h/D as a function of θ_0 for $t/D = 0.03$. The results indicated by "Conventional" in the figures are obtained for the conventional method described in Fig. 1(a). It is apparent from Fig. 2(c) that the refraction angle θ_2 cannot exceed 37.7° for any incidence angle θ_0 which can vary from 0° to 90°. The value of θ_2 is limited because the longitudinal wave speed in the PEEK wedge is larger than that of water. Accordingly, the ultrasonic wave cannot propagate at a height below 0.19 D (see Fig. 3(d)). This analysis shows that when the existing method in Ref. [28] is used, there always is an upper limit on the measurable height of the accumulated sludge which is 0.19 D.

We also note that the wave inside the fluid must travel parallel to the water level to estimate the sludge accumulation level. Therefore, to ensure a parallel wave propagation condition in the water using the existing method depicted in Fig. 2(a), the conditions of equation 4 must be satisfied.

When an L wave is incident through a commonly used conforming PEEK-based wedge onto a plastic pipe, the wave path from the PZT transmitter to the PZT receiver must follow the wave path indicated in Fig. 2(a). Specifically, the generated L wave from the PZT should travel downwards at an oblique angle towards the pipe wall, and the L wave that has traveled through the fluid should travel upwards at an oblique angle towards the PZT receiver. This wave passage may be referred to as the *convex path*.

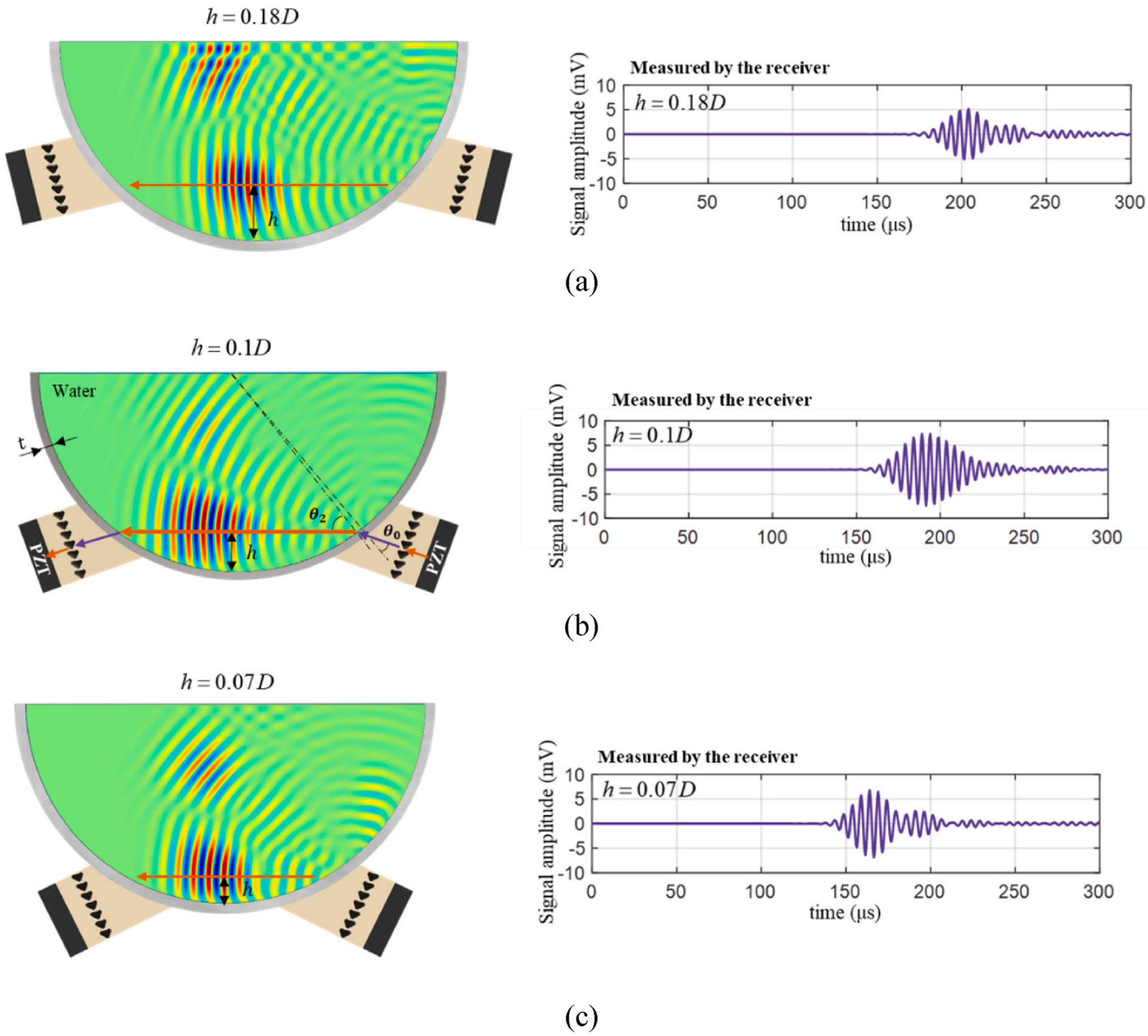


Fig. 6. The wave propagation simulation results (left: snapshots of the fluid inside a plastic pipe; right: time-transient signal received by the receiving PZT unit) using the proposed configuration using meta-slab wedge transducers. The color levels in the plots denote the magnitude of the acoustic pressure. (a) The target wave passage heights are: (a) $h = 0.18D$, (b) $h = 0.1D$, and (c) $h = 0.07D$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

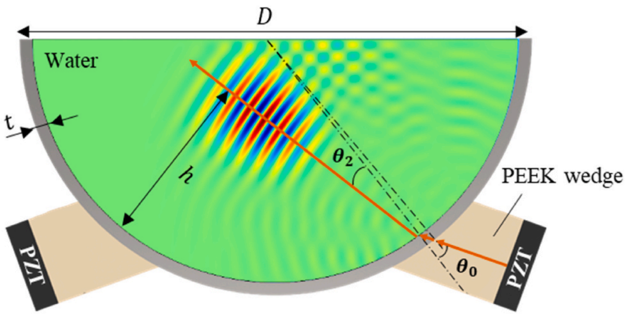
As long as the wave passage described above is used, there is no way to increase further θ_2 and thus reduce h/D. The only way to further reduce h/D is to use the wave passage depicted in Fig. 2(b) which requires using an S (shear) wave in some parts of the wave passage. This is our approach we are proposing in this work, and the details of the working and design principles are explained below.

The proposed wave passage and the transducer installation are depicted in Fig. 2(b). The first important observation from this figure is that the wave passage in Fig. 2(b) is different from that in Fig. 2(a). Here, the generated wave from the PZT travels upwards at an oblique angle towards the pipe wall, and the wave that has traveled through the fluid travels downwards at an oblique angle towards the PZT receiver. We will refer to this wave passage as the *concave path*. In this concave path, the use of the proper wave modes is critical. Before elaborating on further details, we first summarize the wave modes at different locations in the wave passage as shown in Fig. 3:

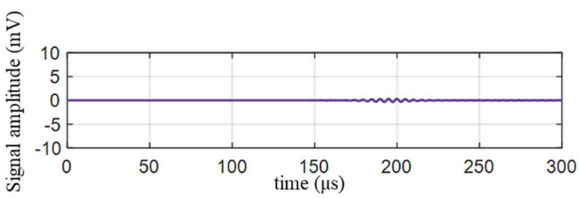
1. Wave mode generated by the transmitting PZT disc: L wave;
2. Wave mode in the PEEK after the wave enters the PEEK before the meta-slab: L wave;
3. Wave mode after the meta-slab of the wedge: S wave (due to perfect mode conversion from L wave to S wave);
4. Wave mode in the PVC pipe when a wave enters it from the wedge: S wave;
5. Wave mode in the fluid: L Wave (due to mode conversion from the pipe to fluid);
6. Wave mode in the PVC pipe when a wave enters from the fluid: S wave (due to mode conversion from the fluid to the pipe);
7. Wave mode in the PEEK wedge before the meta-slab: S wave;
8. Wave mode in the PEEK wedge after the meta-slab: L wave;
9. Wave mode entering the receiving PZT disc: L wave.

The key to achieving the concave path, which will be shown to be critical in lowering the height of the ultrasonic wave path h, is using an S wave in the course of the wave passage. The equations to calculate θ_{11}, θ_{12}, θ_2 and h given as Eqs. (1)–(4) are also valid here, except for the changes in some wave speeds. For a better comparison, we write θ_{11} and θ_2 explicitly for the case of the concave path depicted in Fig. 2(b):

$$\theta_{11} = \sin^{-1}\left(\frac{c_S^{PVC}}{c_S^{PEEK}}\sin(\theta_0)\right) \text{ and} \tag{5}$$



(a)



(b)

Fig. 7. The ultrasonic waves propagate inside the water using a conventional ultrasonic transducer installed at the same location as the meta-slab ultrasonic transducer. (a) A snapshot of the ultrasonic wave propagated inside the water (the color levels in the plots denote the magnitude of the acoustic pressure) and (b) the ultrasound signal received from the receiving PZT unit. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$$\theta_2 = \sin^{-1}\left(\frac{\frac{D}{2}}{\frac{D}{2}-t}\frac{c_L^{Water}}{c_S^{PEEK}}\sin(\theta_0)\right), \tag{6}$$

where the wave speeds with subscript S denote the shear wave speeds. Because c_S^{PVC}/c_S^{PEEK} is not much different from c_L^{PVC}/c_L^{PEEK}, the value of θ_{11} calculated from Eq. (5) will not be much different from that calculated from Eq. (1) as long as the incident angle θ_0 is the same. However, the comparison of Eqs. (6) and (3) shows that the concave path uses c_S^{PVC}, the shear wave speed of the PVC, while the convex path uses c_L^{PVC}, the longitudinal wave speed of the PVC, when the wave from the PVC pipe enters the fluid inside the pipe. Specifically, $c_L^{Water}/c_L^{PEEK} < 1$ and $c_L^{Water}/c_S^{PEEK} > 1$. Therefore, the refracted angle θ_2 in the fluid can be even larger than θ_0 ($\theta_{12} \approx \theta_{11}$) in the case of the concave path, unlike in the case of the convex path. If θ_2 becomes larger, then the value of h can be lower even up to zero.

Fig. 2(c) and (d) show the behavior of θ_2 and h for the concave path, achieved with the meta-slab wedge. Because c_L^{Water} (the longitudinal wave speed of the water) is larger than c_S^{PEEK} (the shear wave speed of the PVC pipe), there exists a critical angle θ_0^{cr} which is 42.2°. If $\theta_0 > \theta_0^{cr}$, $(c_L^{Water}/c_S^{PVC})\sin(\theta_{12})$ becomes larger than unity. This means that the L wave generated by the PZT unit cannot be transmitted to the water. In Fig. 2(c), θ_2 for $\theta_0 > \theta_0^{cr}$ is set to be 90°. On the other hand, one can see that when the incidence angle θ_2 varies between 0° and θ_0^{cr}= 42.2° θ_0^{cr} = 42.2°, the refraction angle θ_2 varies between 0° and 90°. Accordingly, the height of the ultrasonic wave path h can vary from 0 to 0.5D (see Fig. 2(d)). Theoretically, the concave path using an S wave generated by the meta-slab transducer enables the detection of sludge accumulated at any height.

As evident from Fig. 2(c) and (d), the height h of the detectable sludge can be reduced if the speed of the wave in the PVC pipe that enters the water is smaller (at least equal to) than the wave speed in the water inside the PVC pipe. This can be only possible if the shear wave in the PVC pipe is selected as the wave propagating into the PVC pipe because $c_S^{PEEK} < c_L^{Water}$. Therefore, using a meta-wedge that converts the generated L wave by the PZT element to an S wave is critical. To avoid any interference of the converted S wave with the L wave in the remaining part of the wedge, the incident L wave should be converted to a transmitted S wave only. In other words, a perfect mode conversion is necessary. The perfect mode conversion phenomenon was first investigated in Refs. [25,26] and further elaborated in Refs. [27–29] as the bimodal quarter-wave impedance matching theory.

As explained in the caption of Fig. 2(b), the black regions in the meta-slab represent elaborately designed voids fabricated in the base PEEK wedge. The zoomed view in Fig. 4(a) shows the unit cell configuration forming the meta-slab; each unit cell occupies a square region (in the two-dimensional plane) and has elaborately designed voids in the base PEEK material. Referring to Fig. 2(b), the unit cells are repeatedly arranged in the direction perpendicular to the wave propagation, but there is only a single unit cell in the wave propagation direction. While it is common to arrange many unit cells along the wave propagation direction to achieve a metamaterial, the present metamaterial is achieved with a single unit cell to facilitate the actual fabrication. Thus, the actual metamaterial slab can be specifically called a mono-layer metamaterial slab. The actual design of the meta-slab unit cell presented in this study was carried out by parameter optimization in. which the unit cell is assumed to be represented by 9 parameters $L_x, L_y, l_1, l_2, l_3, \theta_1, \theta_2, \theta_3$, and r defined in Fig. 4(a). The specific configuration given in Fig. 4(a) was obtained after several trials but guided by the unit cells presented in Ref. [27] which suggested that the void shape should not be symmetric with respect to the wave propagation direction and its perpendicular direction. The target frequency to achieve the full L-to-S mode conversion was chosen to be 200 kHz. The chosen unit cell configuration in Fig. 4(a) is relatively easy to fabricate because a laser or wire cutting process can be used. The selected values of the 9 parameters after the optimization are also given in Fig. 4(a). The figure also shows the normalized displacement field when an L wave is incident from the left-hand side. For the numerical simulation performed with the COMSOL multiphysics software, we imposed a periodic boundary condition between two boundaries of y=constant. In the plot, u_x and u_y denote the x-and y-directional displacements, respectively. Therefore, they represent the L and S wave fields, respectively. It is apparent from the displacement plots that the incident L wave is fully converted to the transmitted S wave at the target frequency of 200 kHz. Fig. 4(b) shows the mode conversion efficiency quantitatively at the target frequency and adjacent frequencies.

Fig. 4(b) shows that the mode conversion efficiency from an L wave to an S wave by the designed meta-slab is 97.5 % (sufficiently close to 100 %) in power at the target full mode-conversion frequency (f_{FMC}) of 200 kHz. The mode conversion ratio was calculated as the ratio of the transmitted S wave power to the incident L wave power as

$$\text{Mode converting ratio }(\%) = \frac{c_S^{PEEK}}{c_L^{PEEK}}\left(\frac{|u_y|}{u_0^L}\right)^2 \times 100 \tag{7}$$

where u_0^L is the displacement magnitude of the incident L wave. As shown in Fig. 4(b), the efficiency drops at frequencies away from f_{FMC} because the effective properties of the meta-slab are designed to achieve the full mode conversion at the target frequency.

3. Numerical simulations for sludge accumulation inspection

In this section, we present the wave simulation results for the cases of the convex path (using an L wave only) and the concave path (using the proposed L and S wave approach). We start with the case of the convex path and the simulation results are presented in Fig. 5.

For all simulations in this section for both cases, two-dimensional finite element analyses were performed using the COMSOL Multiphysics software. The target frequency f was set as

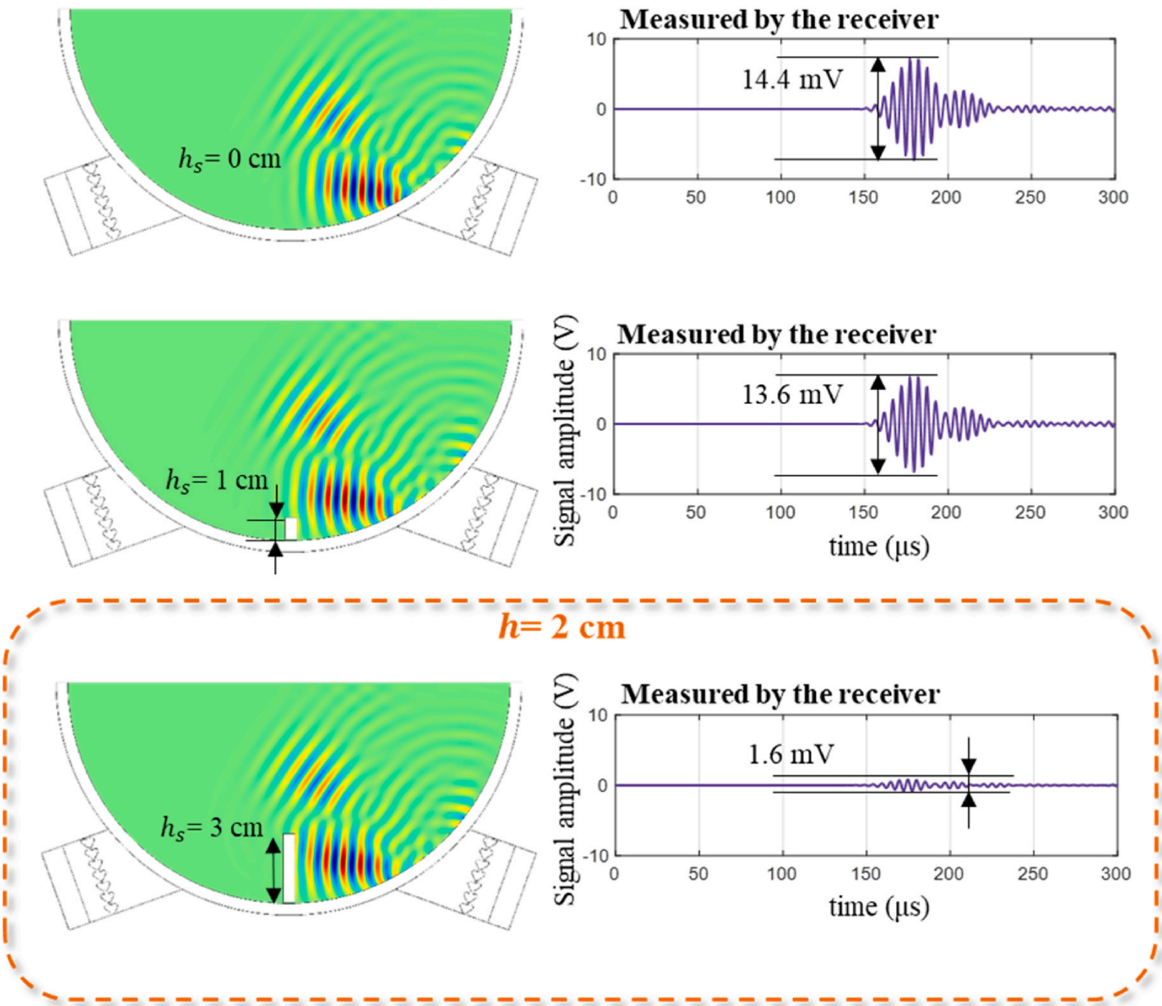


Fig. 8. The finite element simulation results for the concave path (using L and S waves) achieved by the meta-slab transducer (h_s: the height of a rigid block simulating accumulated sludge; h: the height of the horizontally propagating wave in water) the ultrasonic wave path inside the water was set to h = 2 cm.

$f = f_{FMC} = 200$ kHz.

The test pipe was a water-filled PVC pipe with the following dimensions:

D = 200 mm and t = 6 mm (t/D = 0.03).

Ten cycles of a sine wave with its peak-to-peak value of 1 V were sent to the PZT unit in the transmitter (lying on the right hand side of the test pipe).

Fig. 5 presents the simulation results obtained using a pair of conventional transducers in which only an L wave was used throughout the wave passage. We considered three different values of h_s which was the height of a rectangular block used to simulate the sludge accumulated inside the pipe: h_s = 0, 4, and 6 cm. The height h of the ultrasonic wave path was set to $h = 0.25D = 5$ cm, which is slightly higher than the lower limit value of 0.19D. For the selected h, we can use Eqs. (1)–(4) to find the incidence (θ_0) and refraction (θ_2) angles as

$\theta_0 = 50^\circ$ and $\theta_2 = 27.9^\circ$.

If $h_s < h$, the magnitude of the received signal by the receiving transducer is over 60 mV, but when $h_s > h$, it reduces to 12.5 mV which is only 20 % of the signals measured for the other cases. These results show that only when h_s is larger than $h = 0.25D = 5$ cm (more precisely $h = 0.19D$), conventional transducers can be used. For sludge accumulated at a height lower than 0.19D, an alternative approach must be used because the method with conventional transducers is no longer applicable.

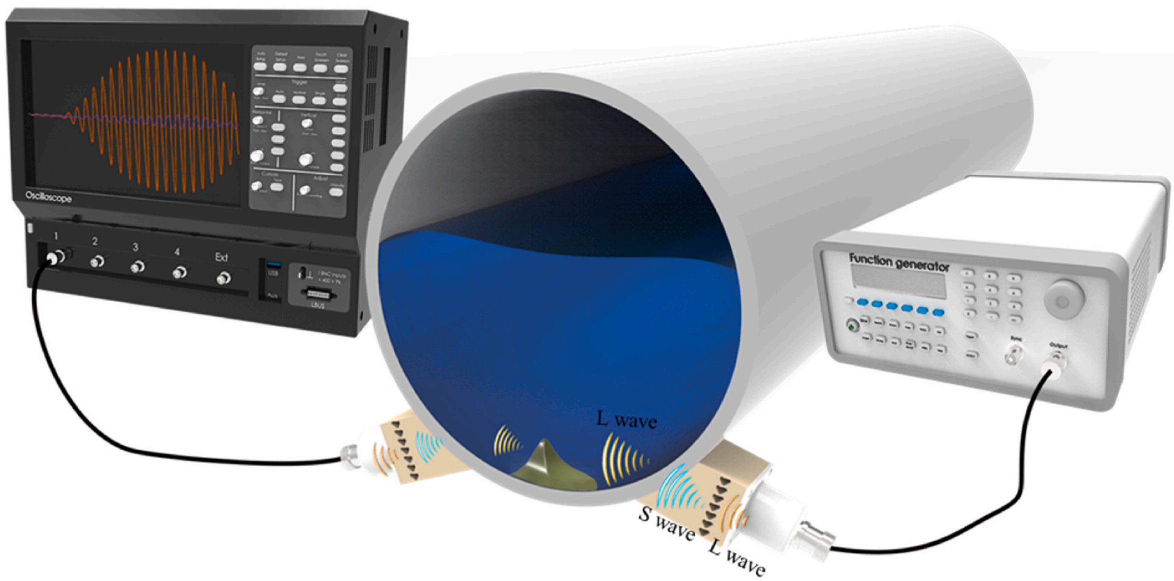
The ultrasonic wave path inside the water was set to h = 5 cm.

Next, we considered the case when the proposed concave path is used. As explained earlier, meta-slab mode-converting wedge transducers should be used to be able to form the concave path. We checked whether an accumulated sludge of height h_s lower than 0.19D could be indeed detected. We present snapshots of the ultrasonic waves propagating inside the water for three different meta-transducer installations targeted at h= 0.18D in Fig. 6(a), h= 0.1D in Fig. 6(b), and h= 0.07D in Fig. 6(c) (The selected heights of the ultrasonic wave passage are lower than 0.19D, the lowest height achieved by the conventional transducer.). The color level denotes the normalized acoustic pressure in water. Note that with Eqs. (1)–(4), one can find the following pairs of the incidence and refraction angles:

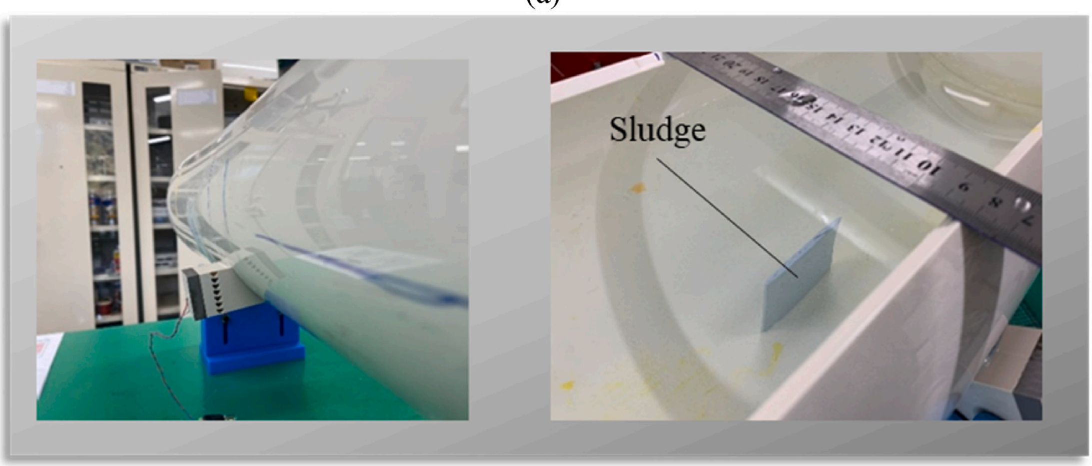
Fig. 6(a): $(h;\theta_0,\theta_2) = (0.18D; 25.3^\circ, 39.1^\circ)$;
Fig. 6(b): $(h;\theta_0,\theta_2) = (0.1D; 31.8^\circ, 51.8^\circ)$;
Fig. 6(c): $(h;\theta_0,\theta_2) = (0.07D, 35.5^\circ, 58.9^\circ)$.

The received signals by the receiving PZT unit are also plotted on the right side of Fig. 6. The simulation results confirm that the dominant ultrasonic waves propagate along the designed path in the fluid inside the pipe. In theory (neglecting actual installation), the minimum value of h can be as low as 0.

It is worth examining what happens if the incidence angle used for the meta-transducer installation in Fig. 6 is used for the conventional



(a)



(b)

Fig. 9. The pitch-catch ultrasonic experimental setup for accumulated sludge detection using a pair of meta-slab transducers enabling the concave path. (a) Overview of the sludge accumulation inspection system for a plastic pipe. It consists of a pair of ultrasonic meta-slab wedge transducers, a function generator, and an oscilloscope. (b) The photos of the meta-slab wedge transducer installed on the outer wall of a PVC pipe.

transducer installation. Specifically, we considered the case of $\theta_0 = 31.8^{\circ}$ (corresponding to the case shown in Fig. 6(b)) for the conventional transducer installation. Simple calculations show that for the conventional transducer installation,

$\theta_2 = 18.8^{\circ}$ and $h = 0.31D$ if $\theta_0 = 31.8^{\circ}$.

Fig. 7(a) shows the installation of the conventional transducer at $\theta_0 = 31.8^{\circ}$ and also the simulation result for the snapshot of the ultrasonic wave propagating in the fluid. When the ultrasonic wave is incident to the pipe in the form of an L wave, the height of the ultrasonic wave path by the conventional transducer installation becomes much higher than that of the meta-slab transducer installation. Thereby, no ultrasonic wave reaches the receiving PZT unit located at the same height on the other side of the plastic pipe wall; see the received signal by the receiving PZT unit in Fig. 7(b).

Next, we investigated the capability of the proposed non-invasive ultrasonic sludge accumulation detection method using a pair of meta-slab transducers. The test pipe was a PVC pipe with $D = 200$ mm and $t = 6$ mm. As in the previous simulations, we used COMSOL Multiphysics. For the simulations, we chose $\theta_0 = 31.8^{\circ}$. For this incident angle, we have

$\theta_2 = 51.8^{\circ}$ and $h = 20$ mm.

The ultrasound signals received by the receiving PZT unit for different heights h_s of accumulated sludge are shown in Fig. 8. For these simulations, we used paraffin as the sludge material because paraffin has similar material properties to the actual sludge accumulated in a semiconductor factory. The height of the sludge was set to $h_s = 0$, 2, and 3 cm. If $h_s = 0$, no sludge is accumulated inside the pipe. When sludge is accumulated, it is assumed to be 1 cm wide. The snapshots of the acoustic pressure in the water are plotted in the figures to show the ultrasound wave passage in the fluid. The simulation results in Fig. 8 indicate that when the height of the sludge h_s exceeds the designed height of the propagation path $h = 2$ cm, the amplitude of the received signal rapidly decreases, nearly down to 1.6 mV, which is much smaller compared to an amplitude of 13.6 mV which is obtained when there is no sludge accumulated. The simulation results confirm that when sludge accumulation blocks the ultrasound propagation passage, one can detect sludge accumulation over a specified value, which is 2.0 cm, in this case.

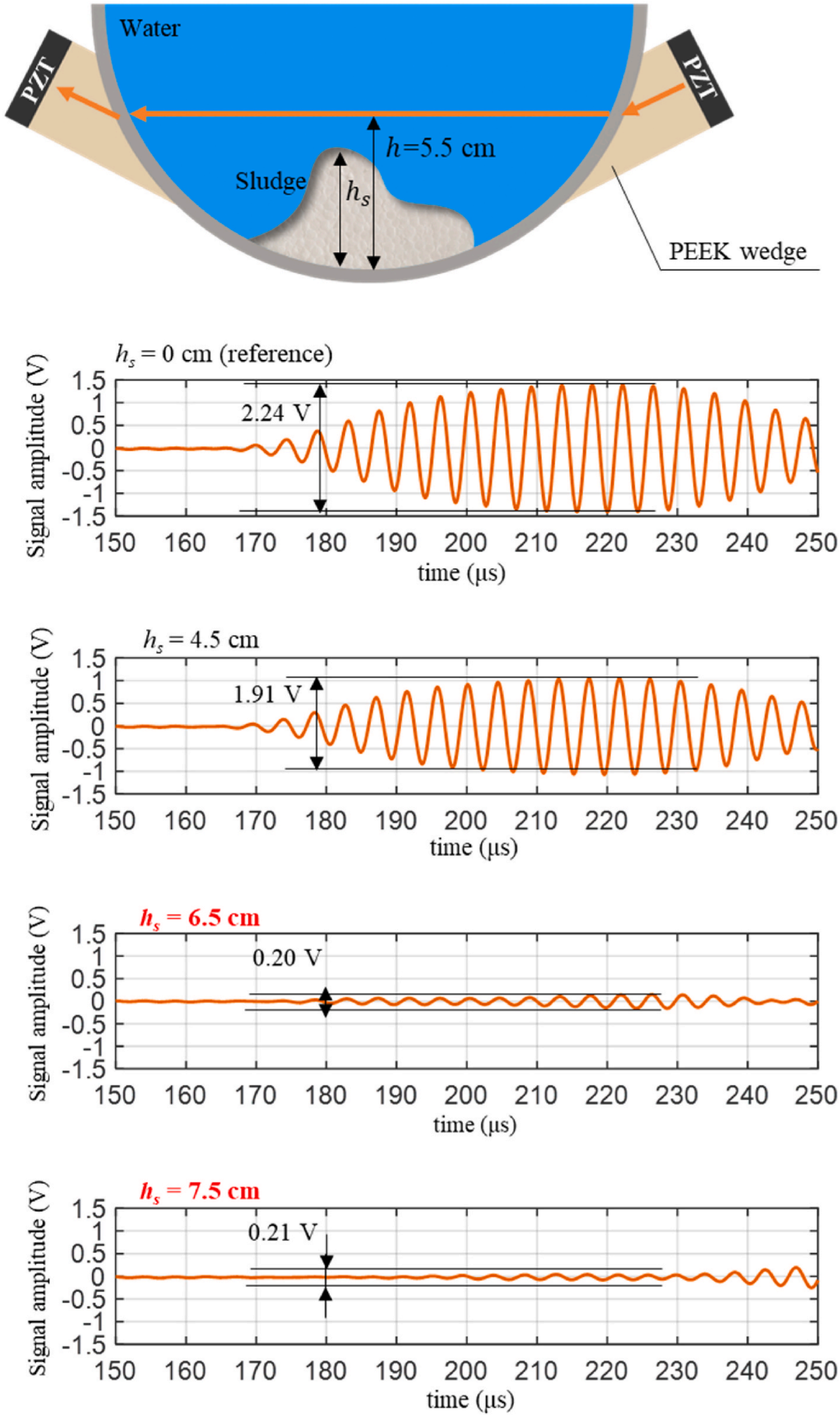


Fig. 10. The experimental results obtained using the conventional wedge transducer with an experimental setup similar to that shown in Fig. 11. The signal amplitudes denote the ultrasound signal (centered at 200 kHz) measured by the receiving PZT unit for various heights h_s. The height h of the wave propagating in the concave path was set to be 5.5 cm.

4. Experimental results

The numerical simulations presented in the previous section indicate that our proposition using ultrasonic meta-slab transducers can dramatically lower the detectable height of sludge accumulated in a fluid flowing inside a plastic pipe compared to the method using the conventional transducer. This section presents experimental results to support our findings from the simulation results.

Fig. 9 shows the experimental setup in which a pair of ultrasonic meta-slab transducers were installed circumferentially on the outer wall of a PVC pipe. To generate 200 kHz waves, 9 mm-thick PZT units were made of PZT-4. A function generator (Agilent 3320 A) sent ten cycles of a

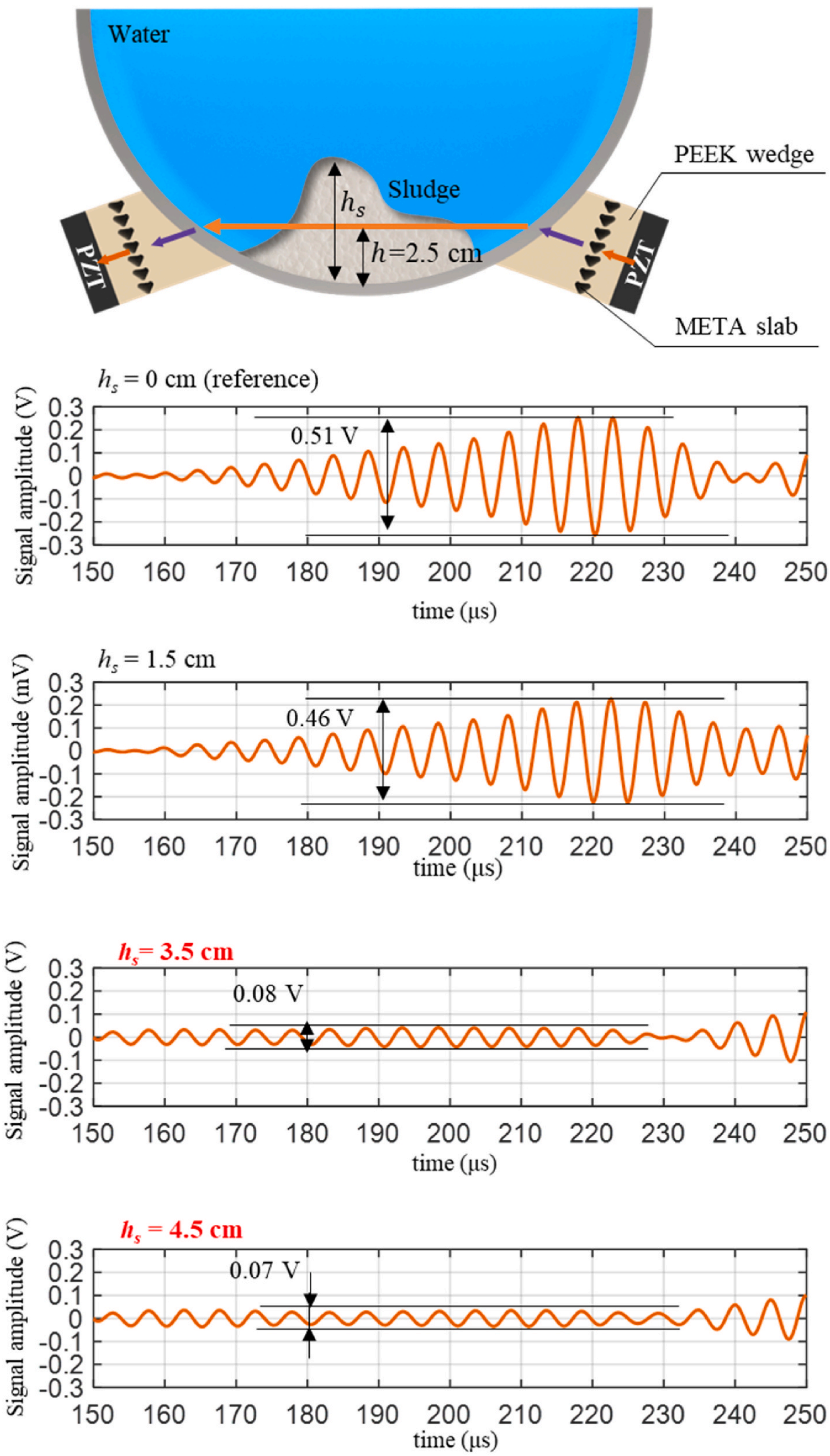


Fig. 11. The experimental results obtained using the meta-slab wedge transducer with the experimental setup in Fig. 11. The signal amplitudes denote the ultrasound signal (centered at 200 kHz) measured by the receiving PZT unit for the various heights h_s. The height h of the wave propagating in the concave path was set to be 2.5 cm.

200 kHz sine signal to the transmitting PZT unit. The magnitude of the peak-to-peak voltage of the signal was 4 V. The ultrasonic meta-slab transducer was coupled with the test PVC pipe using an ultrasonic couplant (SONOTEC 25-012). The ultrasound signal received from the receiving PZT unit was monitored by an oscilloscope (LeCroy WR620Zi). The sludge material we used in the experiment was paraffin wax which has an impedance value (z = 1.35 Mryl) similar to water (z = 1.5 Mryl). For the experiments, a PVC pipe was selected from commercially

available products: $D = 216$ mm and $t = 6.5$ mm.

The height of the ultrasonic wave path for the experiments using the proposed meta-slab wedge transducer method was chosen to be $h = 0.12D = 2.5$ cm, which is slightly higher than the height used in the simulation. For this value of h, the incidence angle θ_0 can be calculated from Eqs. (1)–(4) as $\theta_0 = 30^\circ$. The height of the accumulated sludge h_s was selected as 0, 1.5, 3.5, and 4.5 cm for the sludge height estimation. The height of the ultrasonic wave path for the experiments using the conventional ultrasonic transducer was set to $h = 0.25D = 5.5$ cm. In this case, the incidence angle θ_0 was found to be $\theta_0 = 50^\circ$. The height of the accumulated sludge h_s was selected as 0, 4.5, 6.5, and 7.5 cm.

Figs. 10 and 11 show the experimental results obtained with the conventional and proposed for the various values of h_s, the height of the paraffin wax blocks. Fig. 10 shows that the use of the conventional method exhibits an apparent drop in the magnitude of the signal received by the receiving transducer when $h_s > h = 5.5$ cm. Fig. 11 shows improved detection capability when the proposed method is used. The drop occurs for a smaller value of h, i.e., when $h_s > h = 2.5$ cm. The main difference is that the minimum height of the detectable sludge accumulation can be far lower if the proposed method is used, thus enabling early detection of sludge accumulation inside a plastic pipe.

5. Conclusions

We proposed a non-invasive ultrasonic technique to estimate accumulated sludges at any height inside a plastic pipe using an elaborately designed concave wave path, which was achieved by a pair of meta-slab wedge transducers. While an earlier similar method cannot detect sludge accumulation if the sludge height is higher than $0.19D$ (D: pipe diameter), the measurable height by the proposed method can be much lower than $0.19D$. In theory, it can be as low as zero.

The findings from this study can be summarized as follows:

1. The wave path in the pitch-catch ultrasonic inspection method critically affects the minimum height of the detectable sludge.
2. If the wave mode used remains to be an L wave mode in the whole wave path, as in the conventional approach, only the convex wave path is possible. Thus, the minimum detectable height cannot be smaller than $0.19D$. If both the L and S waves are appropriately used to form the wave path, as used in the proposed method, the desired concave wave path can be formed. Thereby, the detectable sludge height can be smaller than $0.19D$.
3. The use of an S wave contributes to lowering the refraction angle of the wave entering the fluid inside a plastic pipe at a desirable angle which in turn contributes to lowering the detectable sludge height. The meta-slab wedge transducers are designed to fully convert the generated L wave from the PZT units to the S wave.
4. The proposed meta-slab transducers are installed circumferentially on the outer wall of a plastic pipe. Therefore, ultrasound measurements using this setup are insensitive to disturbances originating from the fluid flow.
5. The proposed method can be applied to sludge made of any material because it uses ultrasonic waves in a fluid; as long as sludge can block the wave passage in a fluid, the present method can be applied.

CRediT authorship contribution statement

Chunguang Piao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Jeseung Lee:** Conceptualization, Data curation, Investigation, Software. **Sung Hyun Kim:** Investigation, Validation. **Yoon Young Kim:** Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yoon Young Kim reports financial support was provided by The Korea Ministry of Science. YOONYOUNG KIM has patent APPARATUS FOR MEASURING HEIGHT OF FOREIGN SUBSTANCE IN PIPE pending to 18/274,701.

Data availability

No data was used for the research described in the article.

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References

[1] Piao C, Kim SH, Lee JK, Choi WG, Kim YY. Non-invasive ultrasonic inspection of sludge accumulation in a pipe. Ultrasonics 2022;119:106602.
[2] Lynnworth LC, Liu Y. Ultrasonic flowmeters: half-century progress report, 1955–2005. Ultrasonics 2006;44:e1371–8.
[3] Chen J, Chen S, Li B, Lu J. Research on a transit-time liquid ultrasonic flowmeter under unstable flow fields. Meas Sci Technol 2019;30(5):055902.
[4] Zhang H, Guo C, Lin J. Effects of velocity profiles on measuring accuracy of transit-time ultrasonic flowmeter. Appl Sci 2019;9(8):1648.
[5] Guan R, Lu Y, Wang K, Su Z. Fatigue crack detection in pipes with multiple mode nonlinear guided waves. Struct Health Monit 2019;18(1):180–92.
[6] Hong X, Lin X, Yang B, Li M. Crack detection in plastic pipe using piezoelectric transducers based on nonlinear ultrasonic modulation. Smart Mater Struct 2017;26(10):104012.
[7] Feng Y, Zhang Y, Zheng W. Simulation analysis and experimental study of an alternating current field measurement probe for pipeline inner inspection. NDT E Int 2018;98:123–9.
[8] Chen G, Katagiri T, Song H, Yusa N, Hashizume H. Detection of cracks with arbitrary orientations in a metal pipe using linearly-polarized circular TE11 mode microwaves. NDT E Int 2019;107:102125.
[9] Louati M, Ghidaoui MS. Eigenfrequency shift mechanism due to an interior blockage in a pipe. J Hydraul Eng 2018;144(1):04017055.
[10] Louati M, Ghidaoui MS, Meniconi S, Brunone B. Bragg-type resonance in blocked pipe system and its effect on the eigenfrequency shift. J Hydraul Eng 2018;144(1):04017056.
[11] Mabpa P, Ayundhya PNN, Kunthong J. Clogged pipe detection and monitoring by using acoustic analysis methodology. In: 2020 17th international conference on electrical engineering/electronics, computer, telecommunications and information Technology (ECTI-CON). IEEE; 2020.
[12] Li Y, Feng Z, Huang G, Zhu X. Partial blockage detection in underground pipe based on guided wave&semi-supervised learning. In: 2018 Chinese Control and decision conference (CCDC). IEEE; 2018.
[13] Chu J, Liu Y, Lv X, Li Q, Dong H, Song Y, Zhao J. Experimental investigation on blockage predictions in gas pipelines using the pressure pulse wave method. Energy 2021;230:120897.
[14] Pernía AM, Mayor HA, Prieto MJ, Villegas PJ, Nuno F, Martin-Ramos JA. Magnetostrictive sensor for blockage detection in pipes subjected to high temperatures. Sensors 2019;19(10):2382.
[15] Andrés-Mayor H, Prieto MJ, Villegas PJ, Nuno F, Martin-Ramos JA. Development of magnetostrictive transducer prototype for blockage detection on molten salt pipes. Energies 2018;11(3):587.
[16] Keramat A, Zanganeh R. Statistical performance analysis of transient-based extended blockage detection in a water supply pipeline. J Water Supply Res Technol - Aqua 2019;68(5):346–57.
[17] Datta S, Gautam NK, Sarkar S. Pipe network blockage detection by frequency response and genetic algorithm technique. J Water Supply Res Technol - Aqua 2018;67(6):543–55.
[18] Yang L, Fu H, Liang H, Wang Y, Han G, Ling K. Detection of pipeline blockage using lab experiment and computational fluid dynamic simulation. J Petrol Sci Eng 2019;183:106421.
[19] Yan XF, Duan HF, Wang XK, Wang ML, Lee PJ. Investigation of transient wave behavior in water pipelines with blockages. J Hydraul Eng 2021;147(2):04020095.

[20] Gurav S, Kumar P, Ramshankar G, Mohapatra PK, Srinivasan B. Machine learning approach for blockage detection and localization using pressure transients. In: 2020 IEEE international conference on computing, power and communication technologies (GUCON). IEEE; 2020.
[21] Jafari R, Razvarz S, Vargas-Jarillo C, Geov A. Blockage detection in pipeline based on the extended Kalman filter observer. Electronics 2020;9(1):91.
[22] Zhu X, Feng Z, Huang G. Blocking detection of underground drainage pipe based on CEEMD and GG clustering. In: 2018 Chinese Control and decision conference (CCDC). IEEE; 2018.
[23] Zhao M, Ghidaoui MS, Louati M, Duan HF. Numerical study of the blockage length effect on the transient wave in pipe flows. J Hydraul Res 2018;56(2):245–55.
[24] Abdullahi M, Oyadiji SO. Simulation and detection of blockage in a pipe under mean fluid flow using acoustic wave propagation technique. Struct Control Health Monit 2020;27(4):e2449.
[25] Kweun JM, Lee HJ, Oh JH, Seung HM, Kim YY. Transmodal Fabry-Pérot resonance: theory and realization with elastic metamaterials. Phys Rev Lett 2017;118(20): 205901.
[26] Yang X, Kweun JM, Kim YY. Theory for perfect transmodal Fabry-Perot interferometer. Sci Rep 2018;8(1):1–6.
[27] Yang X, Kim YY. Asymptotic theory of bimodal quarter-wave impedance matching for full mode-converting transmission. Phys Rev B 2018;98(14):144110.
[28] Piao C, Yang X, Kweun JM, Kim H, Park H, Cho SH, Kim YY. Ultrasonic flow measurement using a high-efficiency longitudinal-to-shear wave mode-converting meta-slab wedge. Sensors and actuators. A. Physical 2020;310:112080.
[29] Yang X, Kweun M, Kim YY. Mono-layer metamaterial for full mode-converting transmission of elastic waves. Appl Phys Lett 2019;115(7):071901.
[30] Tian Y, Song Y, Shen Y, Yu Z. A metamaterial ultrasound mode convertor for complete transformation of Lamb waves into shear horizontal waves. Ultrasonics 2021;119:106627.
[31] Tian Y, Shen Y, Qin X, Yu Z. Enabling the complete mode conversion of Lamb waves into shear horizontal waves via a resonance-based elastic metamaterial. Appl Phys Lett 2021;118:014101.
[32] Lee J, Kweun M, Lee W, Park CI, Kim YY. Perfect transmission of elastic waves obliquely incident at solid–solid interfaces. Extreme Mechanics Letters 2022;51: 101606.
[33] Lee J, Park J, Park CW, Cho SH, Kim YY. Uni-modal retroreflection in multi-modal elastic wave fields. Int J Mech Sci 2022;232:107655.

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