Development of Polygonal Buffer Rods for Ultrasonic Pulse-Echo Measurements

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Abstract. In ultrasonic pulse-echo measurement with a long buffer rod (waveguide), it is required to prevent the generation of spurious echoes (often called trailing echoes) accompanying with a main echo in the buffer rod. In this work, new method to prevent such trailing echoes in the rod is proposed and the effectiveness of the method has been demonstrated experimentally and numerically. In the method the cross-sectional shape of the rod perpendicular to the axial direction is a polygon having sides any one of which is not parallel to any of the other sides, so that trailing echoes are hardly generated during the propagation of pulsed ultrasonic wave in the rod. Three-dimensional numerical simulations based on a finite difference method are performed to examine the behaviours of ultrasonic pulse-echoes including trailing echoes for several types of buffer rods having different cross-sectional shapes such as a circle, triangle, square, pentagon, hexagon and heptagon. Based on the results, experiments with several buffer rods are carried out at frequency 5 MHz. It has been found that heptagon may be the suitable shape for effectively eliminating trailing echoes and improving the signal-to-noise ratio of the measured pulse-echo.

1. Introduction
In the several fields of science and engineering, ultrasonic pulse-echo techniques are widely used for materials evaluations and characterizations. It is known for the applications under harsh conditions such as high temperature environments that some high temperature ultrasonic techniques such as laser ultrasonics, EMATs, high temperature transducers and buffer rod method (known as a delay-line or waveguide method) can be available. It is noted that each technique has advantages and disadvantages. Although the buffer rod method is rather classical, it is still an attractive approach from the viewpoints of its simplicity, convenience, robustness and low cost. For very high temperature applications of the buffer rod method, a long buffer rod is often employed as a waveguide. A conventional piezoelectric transducer is installed to the one end of the buffer rod and the other end is in contact with a measuring objective at high temperature. A crucial problem in using such long buffer rods is, in most cases, caused by spurious echoes (known as trailing echoes) due to interference of mode converted waves, dispersion and diffraction within the rod of finite diameter [1, 3, 4]. Such spurious echoes are considered as noise and overlapped with a main echo while pulse-echo measurement is being performed and deteriorate the signal-to-noise ratio (SNR) in the measurement significantly because of their possible interference with a desired signal. To overcome such problem, tapered buffer rods were developed to prevent the generation of trailing echoes [1-3]. It should be noted, however, that such tapering is not always the best solution and may have a difficulty in machining if the rod material is “hard-to-work material” such as hard ceramic materials. In this paper, an alternative method to prevent
such trailing echoes in long buffer rods is proposed and the effectiveness of the method is demonstrated experimentally and numerically.

2. Designing polygonal buffer rods
It is known that trailing echoes appeared in a long buffer rod is mainly caused by interferences of reflected and mode converted waves at the side surface of the rod during ultrasonic wave propagation through the rod [1, 3, 4]. In the case of a cylinder rod whose cross-sectional shape perpendicular to the axial direction is a circle as shown in the left side of figure 1, there exist infinitely many pairs of reflected or mode converted echoes that will constructively interfere with each other depicted by arrows in the figure. This is basically because of axisymmetric shape of the circle. Such interferences make trailing echoes effectively accompanying with a main echo propagating through the rod. Now, we consider different shapes for the cross-sectional geometry, such as triangle or square as shown in the second or the third from the left in figure 1. In the case of square, because of two pairs of parallel sides, there are possibly two pairs of waves to interfere with each other depicted as arrows in the figure, so that it is still expected to produce trailing echoes in the rod. On the other hand, in the case of triangle, there is no possible interference of waves because there is no pair of parallel sides as shown in the figure. Therefore, it is highly expected for the triangle shape to prevent the generation of trailing echoes, owing to less interference of waves. The same thing is true for pentagon and heptagon but not for hexagon. Thus, a polygon having sides any one of which is not parallel to any of the other sides seems to be effective to reduce the formation of trailing echoes. It is predicted that “odd polygons (triangle, pentagon and heptagon)” can effectively restrict the generation of trailing echoes compared to “even polygons (square and hexagon)”.

3. Numerical simulations
Three-dimensional numerical simulations based on a finite difference method are performed to examine the behaviors of ultrasonic pulse echoes including trailing echoes for several buffer rods with different polygonal shapes such as cylinder, triangle, square, pentagon, hexagon and heptagon. Six kinds of buffer rods models with 25 mm in length and approximately 5 mm in diameter are employed as shown in figure 2. The size of ultrasonic transducer is 2.2 mm in diameter and the operating frequency is 5 MHz. A commercial software, Wave 3000 from CyberLogic, Inc. is used for the simulations and 0.03 mm grid size for each model is used to assure the accuracy and stability in the calculation.

![Figure 1. The cross-sectional shapes of polygonal buffer rods. Arrows depicted in each shape show the possible interference waves reflected or mode converted at the side surface of the rod.](image1)

![Figure 2. Three-dimensional models of polygonal buffer rods for the numerical simulations.](image2)
Figure 3 shows the captured images of ultrasonic pulse echoes propagating through the cylinder, square and pentagon rods, where brighter in the image means higher amplitude in the ultrasonic wave. The cross sectional images at a certain position for each echo are also shown under the side view images. As expected, the generation of a trailing echo accompanying with a main echo (first echo) is clearly seen in the cylinder rod as shown in figure 3(a). It is noted that the distance between the main and trailing echoes is about 7.8 mm and almost agree with that estimated theoretically [5]. It can be seen in figure 3(b) that a clear trailing echo is also observed for the square rod and the amplitude of the echo is even larger than that of the cylinder rod. This may be caused by more effective interference of reflected and mode converted waves. Thus, the formation of trailing echoes for such rods are successfully demonstrated with the three-dimensional simulations. On the other hand, no trailing is observed for the pentagon rod as shown in figure 3(c). The similar result is obtained for the heptagon rod. This reveals that the generation of trailing echoes is effectively constrained in “odd polygon” because there is no pair of parallel sides in such odd polygon rods as mentioned in Section 2. This fact is clearly shown in figure 4 showing simulated results of round-trip pulse echoes for all buffer rods.

4. Experimental demonstrations

To demonstrate the validity of the numerical simulation results and the effectiveness of the polygonal rods in eliminating trailing echoes, experiments was carried out for cylinder and polygonal rods with 100 mm in length and approximately 20 mm in diameter. The rods in the experiment are similar in shape to those in the numerical simulation but different in size. Main reason of using small size models in the simulation is time-consuming problem in calculation. It has been confirmed in the simulation that the tendency in the wave propagation behaviour including trailing echoes are almost independent from the rod size as long as the shapes are similar. A 5 MHz ultrasonic transducer of 8 mm in diameter was used for the measurement. Figure 5 shows measurement results of round-trip pulse echoes for the polygonal rods. It can be seen from these results that the tendency in the appearance of trailing echoes for these rods almost agree with that of simulation results shown in figure 4. Although there were some discrepancies in the amplitude of trailing echoes, such quantitative difference may be caused by uncertainty in numerical and experimental conditions. It is noteworthy that the trailing echoes were markedly reduced for the odd polygon rods such as pentagon and heptagon. Thus, the effectiveness of the odd polygon rods in eliminating trailing echoes has been demonstrated.

A remarkable trailing echo was observed for the triangle rod as shown in the second from the top of figure 5. This reveals that unexpected interferences occurred in the triangle rod. It should also be noted here that there exists another remarkable echo for the pentagon rod, depicted by a circle in the forth from the top of figure 5. This echo is quite unpredictable because its location of occurrence is far from the theoretical estimation. Since this unexpected echo was appeared at high reproducibility and independent from measurement conditions, it is likely that this echo was generated owing to the

![Figure 3](image-url)
geometrical feature of pentagon. To examine this prediction, three-dimensional numerical simulations was performed for a pentagon rod of the same geometry as used in the experiment. As the result, a similar echo was observed at the same location as the measured one, as depicted by a circle in figure 6. The further studies are needed to examine the formation of such echoes.

5. Conclusions
A new method to prevent trailing echoes in long buffer rods is proposed and the effectiveness of the method is demonstrated experimentally and numerically. In the method the cross-sectional shape of the rod perpendicular to the axial direction is a polygon having sides any one of which is not parallel to any of the other sides. It has been found that odd polygons such as pentagon or heptagon are suitable shape for effectively eliminating trailing echoes. Further studies are needed to design an optimum buffer rod suitable for pulse echo measurements with a high signal-to-noise ratio.

6. Acknowledgment
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7. References
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