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Designing Tapered Buffer Rod with Small End for Ultrasonic Pulse Echo Measurements

超音波パルスエコー測定用の小さい先端のテーパーバッファーロッドの設計

Yuya Ogawa [1†], Ikuo Ihara [2]
([1] Grad. School of Nagaoka Univ. Tech.; [2] Nagaoka Univ. Tech.)
小川　裕也 [1†]，井原　郁夫 [2] ([1] 長岡技術科学大学大学院, [2] 長岡技術科学大学)

1. Introduction

Ultrasonic pulse echo methods have been widely used for nondestructive mesurements and evaluations in the various fields of science and engineering. The methods are also available for online monitoring and *in-situ* observations of materials and structures in hazardous environments such as high temperatures. In the methods, a long rod is often employed as a waveguide so that a conventional ultrasonic transducer used for such high temperature measurements can be effectively protected from high temperature or hazardous environments. The problem in ultrasonic pulse-echo measurements using such buffer rods is that significant spurious echoes (often called trailing echoes) are generated owing to interference of mode converted waves within the rod.

To overcome the problem, tapered buffer rods were proposed and its high performance to reduce the trailing echoes due to the geometrical effect of tapering was demonstrated successfully[1)]. It was also shown that clad buffer rods consisting of a core rod and a cladding layer provides suitable pulse echo measurements with a high signal-to-noise ratio [2, 3)]. Such buffer rods were successfully applied to several materials measurements at high temperatures [4, 5)]. Recently, a polygonal buffer rod has been applied to molten polymer to measure not only the ultrasonic velocity and attenuation of the molten polymer but also the solid/liquid interface during solidification process of the polymer [6)]. It is expected to apply the buffer rods for making high spatial resolution measurements in some practical application.

In this work, tapered buffer rod with probing end of small diameter has been studied numerically, to understand and confirm the limit of the smallest diameter of the probing end that provides pulse echo measurements. Because the taper angle is the most sensitive parameter influencing the wave propagation in a buffer rod [7, 8)], the effects of the taper angle and the diameter of the probing end on the ultrasonic pulse waves in tapered buffere rods are examined.

ihara@mech.nagaokaut.ac.jp

2. Method

A two-dimensional voxel-based finite element method (FEM) software commercially available (ComWave™ from ITOCHU Techno-Solution Co.) is employed for numerical simulations of ultrasonic pulse wave propagation. **Figure. 1** shows a geometrical shape of a tapered rod model used for the FEM analysis. The material of the rod is polybenzimidazole (PBI). Uniform isotropic voxel element is used for modeling. To ensure successful and accurate wave propagation analysis, the voxel element size is decided to be 30 μm which is less than 1/20 of the shortest wavelength in the analysis. A displacement in the form of 2 MHz cosine function (Mexican hat function) is induced to the center area of the left end surface of the rod so that longitudinal waves could be generated and propagate in the rod. The excited area of the displacement is 12.7 mm. It is noted that the rod end diameter d and the taper angle α are independently changed in the analysis to examine their effects to the pulse echo propagations.

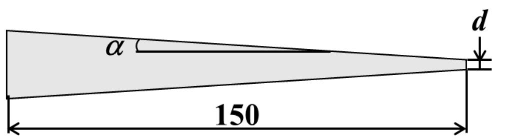

Fig. 1 Geometrical shape of a tapered buffer rod for FEM analysis.

3. Results

Figure. 2 shows a snapshot image of ultrasonic waves propagating in the taper rod with the probing end diameter of 1.49 mm ($d = \lambda$) and taper angle $\alpha = 5^{\circ}$, where d and λ are probing end diameter and a wavelength, respectively. The 1st main echo and following mode converted waves are observed.

Figure. 3 shows the pulse echoes of tapered rods with the probing end diameter of 7.46 mm ($d =$

5λ) for different taper angles. The broken lines depicted in the figure show the transit times corresponding to the 1st and 2nd echoes calculated from the ultrasonic velocity of the rod material (PBI). As expected, remarkable trailing echoes are generated in the straight rod (without taper). By introducing the taper trailing, the trailing echoes are effectively reduced and the 1st and 2nd echoes are clearly observed. On the other hand, the results for the rods with the probing end diameter of 1.49 mm ($d = \lambda$) shown in **Figure. 4** are quite different from those in **Figure. 3**, i.e., the 1st main echoes are hardly observed, and significant spurious echoes different from trailing echoes are observed after the 1st main echoes. It is considered that such spurious echoes may be caused by mode converted waves at the side surface of the rod. Therefore, non-reflective surface is introduced on the side surface in the estimations. As the results, the spurious echoes are disappeared as shown in **Figure. 5**. It should be noted here that clear 1st echo is observed in each tapered rod even though the probing end diameter of the rod is the same size as a wavelength. This reveals that a tapered buffer rod tuned as a proper tapering angle provides high spatial resolution measurements with a high signal-to-noise ratio.

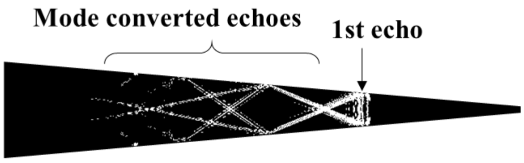

Fig. 2 Snapshot image of the ultrasonic waves traveling to the right in the rod ($d = \lambda$).

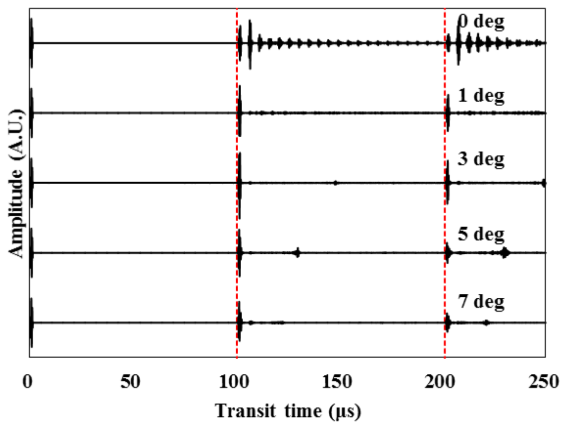

Fig. 3 Ultrasonic pulse echoes of tapered buffer rods ($d = 5\lambda$) for different tapering angles.

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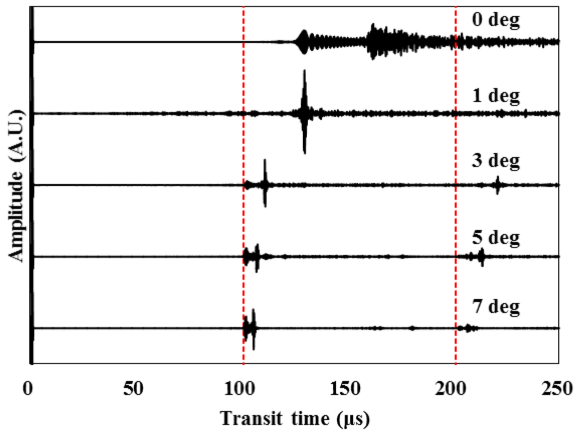

Fig. 4 Ultrasonic pulse echoes of tapered buffer rods ($d = \lambda$) for different tapering angles.

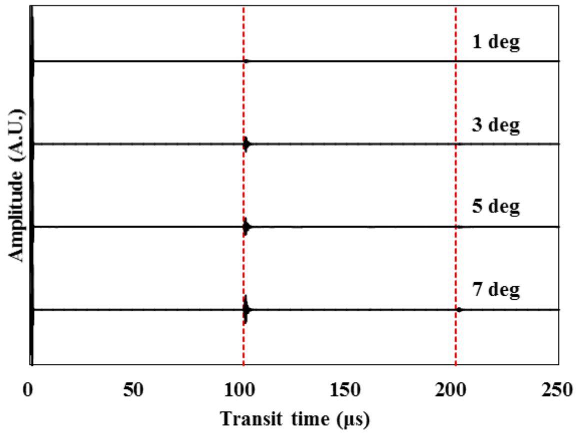

Fig. 5 Ultrasonic pulse echoes of tapered buffer rods ($d = \lambda$) for different tapering angles, where non-reflective surface is introduced on the sides of the rod.

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