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Numerical study of the use of focused ultrasound waves by the phased array method in the inspection of polyethylene pipe joints

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Abstract

Inspection of polyethylene pipe connections is very important in various industries due to its many applications in water, gas, and chemical transmission networks. Among the non-destructive inspection methods, the ultrasonic method is the most suitable method for this type of connection. Due to the polymer material of these connections and a result of the high attenuation of the wave, this type of inspection is associated with challenges. Using the phased array ultrasonic inspection method due to the focus of the wave and creating high-energy points at the joints is an alternative solution to the usual ultrasonic inspection techniques. In this paper, using the finite element method, Ultrasonic inspection is simulated by the usual method and also by the phased array method for monitoring the connections of polyethylene pipes. Some kinds of possible defects have been investigated and their effect on the reflection signal has been determined. Using the numerical method based on successive simulations, the reflection signal has been analyzed in the Phased array method. The results showed that the increase in the number of piezoelectric increased the performance of the inspection as well as an increase in the concentration of the mechanical wave up to 160% for 32 elements and 270% for 64 elements compared to the probe with 16 piezoelectric elements.

Keywords: Polyethylene pipes; Electrofusion welding; Non-destructive inspection; Ultrasonic; Phased array methode

1. Introduction

Suitable mechanical strain, high corrosion resistance, low weight, and ease of connection method have made polyethylene pipes a good alternative for many applications such as water, oil, gas, and chemical materials transmission [1]. Among welding methods, the electrofusion welding method is suitable to connect this kind of pipe. Despite the advantages of this method, such as simplicity and high speed, this type of connection is prone to various defects, such as vacuum, wire dislocation, contamination, poor connection interface, and cold weld. Therefore, connection inspection is essential for polyethylene pipes.

Destructive inspection methods are widely used to inspect this type of connection. Despite the simplicity, low equipment requirements, and high reliability, this inspection method can only apply to limited connections. Therefore, it seems necessary to use non-destructive methods. According to the structure and geometry of the connection, the type of pipes, and their application, the ultrasonic non-destructive test method is a good alternative. However, the significant loss of mechanical waves in polyethylene in polyethylene is an essential limitation for conventional ultrasonic non-destructive test techniques. Using recent techniques to focus the wave, such as the phased array, can reduce this limitation [2].

Many reports existed in connection with the use of the ultrasonic phased array technique to inspect polyethylene joints. Among them, we can use this technique for butt joints of polyethylene pipes by Frederick et al. in 2010[3], optimization of fuzzy array parameters in the inspection of this type of joints by Zhang et al. in 2016[4], and the use of machine learning algorithms by Niu et al. pointed out in 2023[5].

Despite the significant research background in this topic, inspection with high reliability in polyethylene joints still faces many challenges. Sound wave losses cause ambiguity in reflected signals and phased array images. In this article, using the finite element method, applications of the ultrasonic phased array techniques for the inspection of polyethylene joints were simulated, and results were compared with a numerical study of the pulse-echo ultrasonic non-destructive techniques. Besides that, the effect of increasing the phased array elements number on the inspection was investigated, and its results were presented quantitatively. The results showed that increasing the number of elements, although it increases the detection power, makes signal processing difficult and increases the probability of calculation errors. Therefore, for each type of application, an optimal geometry with a certain number of elements according to inspection standards is a more suitable choice.

2. Finite element model

In this paper, pulse-echo and phased array techniques among ultrasonic non-destructive inspection techniques were numerically studied. In both, simulations were performed on a similar polyethylene pipe and coupling geometrical model. Based on the result independent of the element size study, the element size is equal to at least one-tenth of the wavelength to achieve high accuracy in the simulations. Due to the size of the pipe and coupling, increasing the number of elements causes an increase in the volume of calculations and data collection. Increasing data makes their analysis and interpretation more complicated. Tolerating this complexity not only does not increase the accuracy of the simulation but also confuses the interpretation of the results. On the other hand, according to the dimensions of the pipe, its curvature can be ignored, and the model can be reduced to two-dimensional. Therefore, in this article, the numerical model was assumed and modeled in two-dimensional form. According to the geometry of the problem, half of the model was considered in the simulation. Figure 1 shows the model. In the upper border, according to Figure 1, areas were created, which are the places where the vibrations of the piezoelectric rings are applied. A little lower than the position of the piezoelectric (the size of two rows of elements) was created by partitioning the points that were considered as wave receivers in the stage of saving the results.

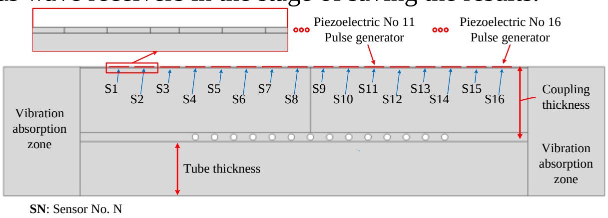


Figure 1. Pipe and coupling model.

Table 1 shows the characteristics of materials required for simulation, including the properties of polyethylene, based on the Kelvin-Voight model, as well as the properties of copper wire.

Table 1. Material properties

Material	Density ($\frac{kg}{m^3}$)	Young modulus (GPa)	$\bar{k}_i^P$	τ_i^G
PE100[6]	942	1.12676	0.564	4348
Copper [7]	8960	128		

In this paper, two ultrasonic inspection techniques for polyethylene pipe joints consisting of pulse-echo and phased array were numerically studied. According to the conditions of the problem, the two-dimensional model with the plane strain assumption was used for simulations. In the phased array excitation, the piezoelectric was divided into groups of four, where a group of piezoelectric is excited with a delay compared to other piezoelectric of the same group. After turning on one batch, the next batch is on. Equation 1 shows the mentioned delay time value [8]. The parameters of Eq.1 are depicted in Figure 2. In the pulse-echo analysis, a single element of the piezoelectric was considered as an ultrasonic probe. In both categories, the material properties are the same.

$$t_n = \frac{F}{c}\left(1 \mp \left(\sqrt{1 + (\mathrm{A}^2 - \mathrm{B})}\right)\right) + t_0$$
$$\mathrm{A} = \left(\frac{d}{F}\left(n - \frac{(N-1)}{2}\right)\right) \quad (1)$$
$$\mathrm{B} = \frac{2d}{F} \sin\theta_s \left(n - \frac{(N-1)}{2}\right)$$

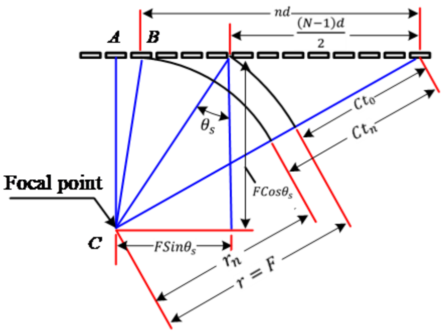


Figure 2. Delay time calculation [8].

The four-node CPE4R first-order linear element was used for meshing. The reduced integral method has been used for the used element to enhance precision. After considering the non-dependence of the response on the element size, the number of 250,000 elements was considered in the simulation.

3. Results and Discussion

The results of the simulation of connection inspection by the ultrasonic pulse-echo technique are shown in Figure 3. As can be seen in this figure, due to the significant losses in polyethylene, the backwall echo amplitude is very low and causes the inspection unreliable.

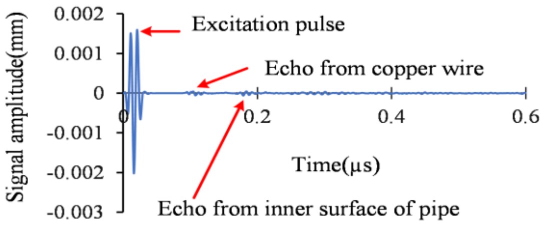
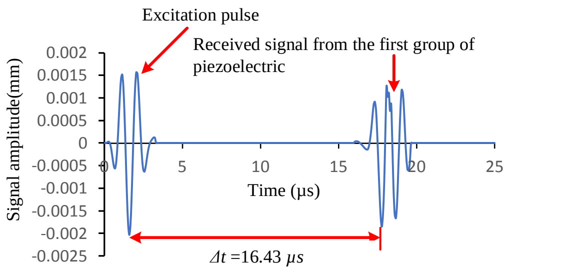


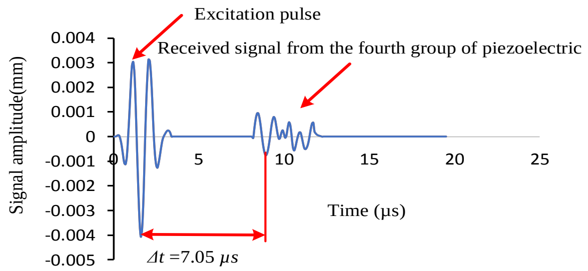
Figure 3. Pulse-Echo signal.

In the case of the phased array probe, the received Echo must be processed in terms of time and determined by the superposition of echoes. After processing the signal for the simulation of the first group of piezoelectrics and the fourth group of piezoelectrics, inspection echoes were obtained according to Figure 4 and Figure 5, respectively. According to Figure 4, the received wave of the first group of piezoelectrics is obtained from the inner surface of the pipe. In the model, the thickness is equal to 20.2 mm. Considering the time of flight, which is equal to 16.43 microseconds, the speed of sound obtained in the simulation is equal to 2460 m/s which shows a difference of one percent with the speed of sound of polyethylene. According to Figure 4, according to the speed of 2460 m/s and the time difference shown, the defect position was obtained as 8.67 mm. Considering that the position of the modeled defect is equal to 8 mm compared to the external surface of the coupling, the error in calculating the position of the defect is 8.3%. A summary of validation results is presented in Table 2.



a

Figure 4. Received signal from the first group of piezoelectric.



b

Figure 5. Received signal from the first group of piezoelectric

Table 2. Verification of simulation

	Exact value	Numerical evaluation
Sound speed($\frac{m}{s}$)	2434[9]	2460
Defect Position(mm)	8	8.76

To study the effect of the number of piezoelectric elements, the simulation with the described procedure was performed for the phased array probe with 32 and 64 elements. Figures 6 and 7 show the results of these simulations. As shown in the figures, increasing the number of elements increases the amplitude of the return echo signal, thus increasing the reliability of the simulation. At the same time, the inspection time increases, and the cost of the probe and the cost of calculations also increase accordingly with the increase in the number of elements.

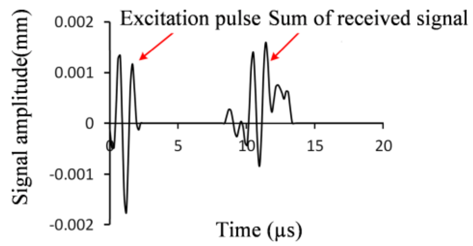


Figure 6. Echo superposition for probe with 32 piezoelectric element

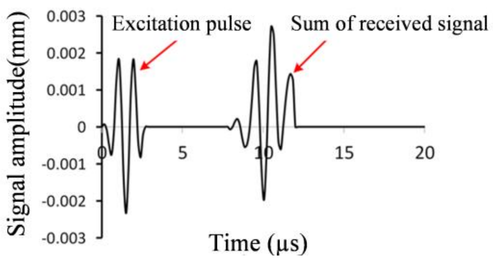


Figure 6. Echo superposition for probe with 64 piezoelectric element

4. Conclusions

In this paper, a numerical approach was exploited to evaluate the ultrasonic method in the troubleshooting of polyethylene pipe joints. With the help of a numerical approach, two pulse-echo and phased array techniques were studied and compared. The results showed that due to the high damping of mechanical waves in polyethylene, the use of conventional pulse-echo wave methods is not suitable. Using the phased array method with four piezoelectric elements, compared to the pulse-echo method based on one piezoelectric element, increases the concentration of mechanical waves by 134%. In the phased array method, the time interval between the excitation of the piezoelectric bunches is very important. If the time interval is short (or inappropriate), wave interference and, as a result, a lot of noise in the received signal will occur. Increasing the number of piezoelectric will increase the performance of the probe and increase the focus of the mechanical wave up to 160% for 32 elements and 270% for 64 elements compared to the probe with 16 piezoelectric elements. On the other hand, increasing the number of elements will increase the amount of calculations and also increase the cost of construction, and make the electrical system more complicated. It seems that according to the inspection, an agreement should be made between increasing the number of elements and also the volume of calculations in the design.

5. Acknowledgement

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