

# ULTRASONIC GUIDED WAVE FOCUSING BEYOND WELDS IN A PIPELINE

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**ABSTRACT.** Ultrasonic guided wave inspection techniques are well-known for the inability to scan a long range axial distance of a pipe from a single transducer position. A phased array focusing technique was developed to improve the ultrasonic guided wave inspection results by concentrating the energy onto a defect. Focusing can increase the energy impinging onto the defects, reduce false alarm ratio, locate the defects, and enhance the propagation distance of the guided waves. An ultrasonic system with  $n$  ( $n > 1$ ) individual excitation channels is required to achieve phased array focusing. When phased array focusing was carried out, time delays and amplitude factors were applied to control the input signals for each excitation channel. Different from the time delays for bulk wave linear array focusing, the time delays and amplitude factors for guided wave array focusing are non-linear functions of the focal distance, the pipe size, excitation conditions, and the active frequency. A challenge of this technique is to focus beyond welds, defects, or other obstructions. The influence of axisymmetric welds is investigated with 3D FEM simulations and an experimental example. The theoretical analysis and experiments shows that although welds usually decrease the penetration energy, a limited number of welds rarely affects the phased array focal location.

**Keywords:** guided waves, focusing, weld, pipe, ultrasonics, phased arrays

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## INTRODUCTION

Recently, ultrasonic guided waves are widely used in pipeline inspection. The guided waves have the property that they can travel a long distance with minimal attenuation and therefore offer the potential of testing large areas from a single point using a pulse-echo transducer bracelet wrapped around a pipe. In order to improve the inspection potential of the guided waves, a phased array focusing technique was developed by Li and Rose [1]. By applying time delays and amplitude factors to a multi-channel transducer array, the ultrasonic energy can be focused at a predetermined spot. The input time delays and amplitude factors depend on the excitation conditions, frequency, and the properties of the pipe. The analytical calculations of these input parameters are based on the research of Gazis [2] and Ditri and Rose [3]. The phased array focusing technique has shown that it can enhance the inspection potential, reduce the false alarm ratio, and increase the working distance of guided waves [4].

However, analytical simulations of phased array focusing are achieved by assuming that the target pipe involves an axisymmetric geometry and elastic isotropic materials. Since many pipes have non-axisymmetric branches, elbows, viscoelastic coatings or

anisotropic welds, it is important to investigate the phased array focusing potential for these pipes. In this paper, the numerical three-dimension finite element method (FEM) simulation and experimental verifications are carried out to study focusing beyond several welds in a pipe.

## CALCULATIONS OF THE FOCUSING PARAMETERS

Guided waves in tubular structures include two major types: 1) longitudinal modes and 2) torsional modes. There are usually several mode groups existing at a particular frequency. Each group involves infinite non-axisymmetric modes (also known as flexural modes) and one axisymmetric mode [5]. L(m,n)/T(m,n) notation is employed to indicate a guided wave mode. The n is the order number of a mode group and the m is the order of an individual mode. When m=0, L(m,n) or T(m,n) implies an axisymmetric mode; when m>0, it represents a non-axisymmetric mode.

In a reference of cylindrical coordinates, Gazis [2] described the particle velocity field of guided waves in pipes as follows:

$$\begin{aligned} v_r &= R_r^{mn}(r)\Theta_r^m(m\theta)e^{i(\omega t - k^{mn}z)} \\ v_\theta &= R_\theta^{mn}(r)\Theta_\theta^m(m\theta)e^{i(\omega t - k^{mn}z)} \quad (m = 0, 1, 2, \dots; n = 1, 2, 3, \dots) \\ v_z &= R_z^{mn}(r)\Theta_z^m(m\theta)e^{i(\omega t - k^{mn}z)} \end{aligned} \quad (1)$$

where  $k^{mn} = \frac{\omega}{c_{mn}}$  is the wave number of the  $m$ th circumferential order of the  $n$ th mode group;  $c_{mn}$  and  $\omega$  are the velocity and angular frequency;  $t$  is the time;  $R_\alpha^{mn}(r)$  and sinusoidal functions  $\Theta_\alpha^m(m\theta)$  ( $\alpha = r, \theta, z$ ) represents the radial and circumferential velocity components in the  $r, \theta, z$  directions.

By applying a partial longitudinal excitation condition:

$$\hat{T} \cdot \vec{n}_r = \begin{cases} -p_1(\theta)p_2(z)\vec{e}_r, & |z| \leq L, |\theta| \leq \alpha, r = b \\ 0, & |z| > L, \text{ or } |\theta| > \alpha, \text{ or } r \neq r_{n+1} \end{cases} \quad (2)$$

or a shear horizontal excitation condition:

$$\hat{T} \cdot \vec{n}_\theta = \begin{cases} -p_1(\theta)p_2(z)\vec{e}_\theta, & |z| \leq L, |\theta| \leq \alpha, r = b \\ 0, & |z| > L, \text{ or } |\theta| > \alpha, \end{cases} \quad (3)$$

Li and Rose [6] and Sun et al. [7] obtained the amplitude function  $A_+^{mn}(z)$  ( $z \geq L$ ) for the  $m$ th mode in the  $n$ th longitudinal or torsional mode group. By utilizing  $A_+^{mn}$  as the weight function of each wave mode in a group, the circumferential displacement distributions (known as angular profiles) of a guided wave group at a certain axial position of a pipe can be calculated.

For a multi-channel guided wave generation system, if every channel has the same excitation conditions as equation (2) or (3), the focused angular profile function  $G$  at a particular distance is obtained by the following formula:

$$G = A \otimes H \quad (4)$$

where the complex function  $A$  is a unknown discrete weight function;  $\otimes$  is the convolution operator;  $H$  is the discrete angular profile function generated by one single excitation element.

In the case of focusing, the  $G$  is 1 at the focal spot. Consequently, the complex discrete weight function  $A$  can be calculated as:

$$A = 1 \otimes^{-1} H = FFT^{-1}(1/H) \quad (5)$$

where  $\otimes^{-1}$  and  $FFT^{-1}$  denote deconvolution and the inverse fast Fourier transform operator. The input phase delay  $\phi_i$  and the amplitude factor  $C_i$  for the  $i$ th excitation channel are the phase and amplitude of the corresponding weight function  $A_i$ . Hence, the time delays for each channel input are:

$$\Delta t_i = -\phi_i / 2\pi f \quad (6)$$

## FINITE ELEMENT SIMULATIONS

The behaviors of the ultrasonic waves are strongly influenced by the highly oriented austenitic welds, so the analytical calculation for elastic isotropic materials is no longer practical [8]. Therefore, a commercial FEM software, ABAQUS, was used to simulate the guided wave propagation in a welded pipe. The pipe welds are assumed to be of 316L industrial austenitic stainless steel. The schematic cross section perpendicular to the welding direction can be seen in Figure 1. The width of the weld at the outer surface of a pipe is about one half inch; the weld width at the inner surface is approximately a quarter inch. These welds are reasonably considered as transversely isotropic media, which becomes isotropic in the  $\theta$ - $z$  plane. The material properties are presented by Chassignole et al [9], as shown in equations (7)-(8).

The Hooke's Law for the weld can be illustrated as follows:

$$[C] = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & 0 & 0 & 0 \\ C_{1122} & C_{2222} & C_{2233} & 0 & 0 & 0 \\ C_{1133} & C_{2233} & C_{3333} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{2323} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{3131} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{3131} \end{bmatrix} \quad (7)$$

$$\begin{aligned} C_{1122} = C_{1133} = 139GPa, \quad C_{2222} = C_{3333} = 233GPa \\ C_{2233} = 100GPa, \quad C_{1212} = C_{3131} = 106GPa \\ C_{1111} = 194GPa, \quad C_{2323} = (C_{3333} - C_{2233})/2 = 65GPa \end{aligned} \quad (8)$$

Figure 2 shows that a 35kHz T(m,1) guided wave group was focused at 114" from the transducer array. The wave guides are 12" scheduled 40s steel pipes (Outer diameter = 12.75"; wall thickness = 0.375"). The input time delays and amplitude factors are calculated by utilizing equations (5) and (6). Applying these time delays and amplitude

factors to control the input signals for the excitation channels forces the ultrasonic energy to be focused at the right position. Figure 2(a) demonstrates the energy focal spot at  $z = 114''$  in a 12'' steel pipe that has no weld. Figure 2(b) and 2(c) show that the ultrasonic energy was correctly focused at the same position, after the guided waves propagated beyond one or two welds. According to the numerical simulations, the absolute value of the torsional-torsional reflection coefficient at a 316L industrial austenitic stainless steel weld was:  $|R| = 0.08$ .

The angular profiles at the focal position ( $z = 114''$ ) are illustrated in Figure 3. Figure 3(a) shows a normalized focused angular profile obtained by employing analytical calculations for an elastic isotropic pipe. Figure 3(b) shows the same angular profile that was calculated by the 3-D FEM method. The black dashed lines show where the energy dropped 6dB from the focal point. By comparing Figure 3(a) and 3(b), one can see that the FEM simulations matched the analytical calculations quite well. Figure 3(c) and 3(d) are the focused angular profiles when the energy was focused beyond one or two welds. When focusing beyond several austenitic transversely isotropic welds, the guided waves still achieved great focal results, almost the same focused angular profiles as before a weld.

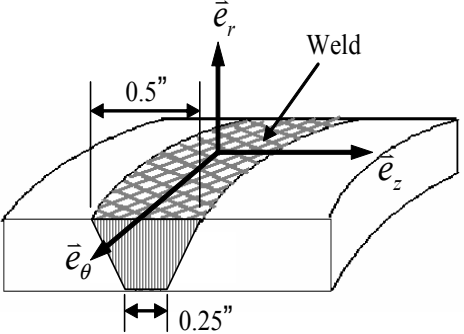


FIGURE 1. Scheme of the 316L industrial austenitic stainless steel welds in a pipe.

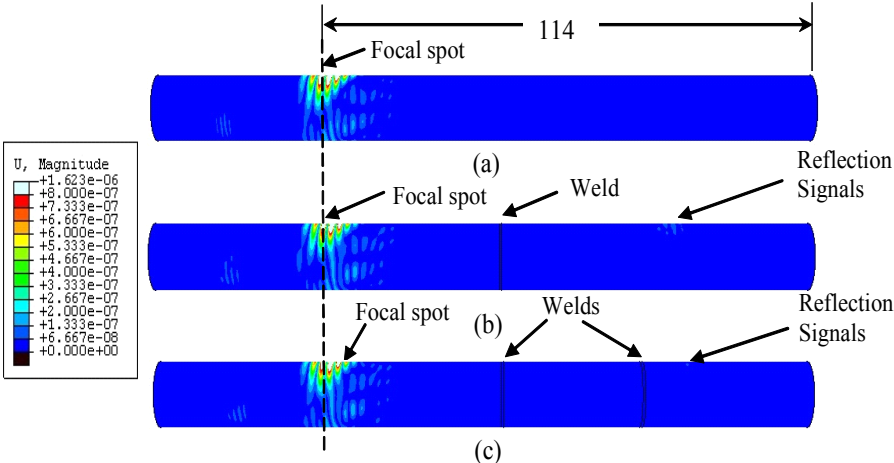
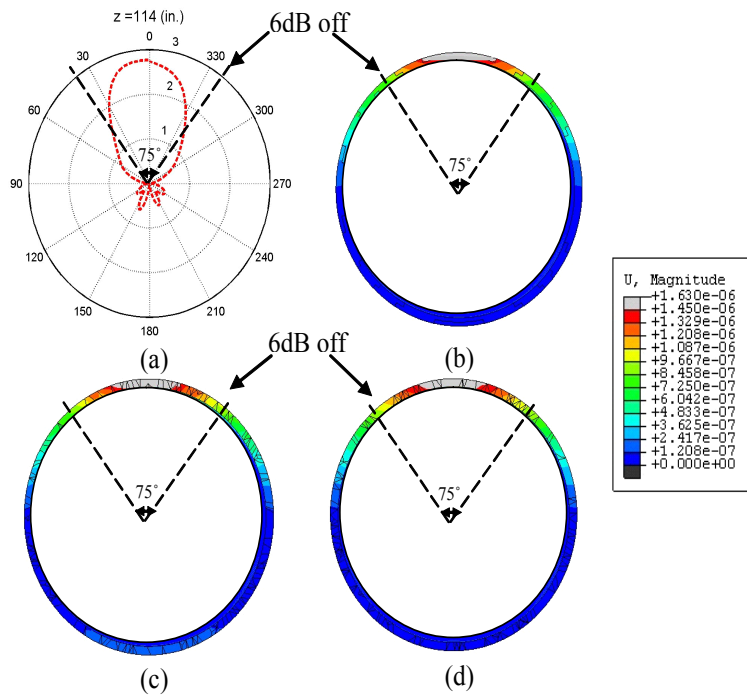


FIGURE 2. 3D FEM simulations of the T(m,1) mode group focusing at  $z=114''$  on the top of a 12'' scheduled 40s steel pipe. The frequency is 35kHz. There are three different pipes: (a) a 12'' scheduled 40s pipe without weld, (b) a 12'' scheduled 40s pipe with a weld at  $z=66''$ , and (c) a 12'' scheduled 40s pipe with two welds at  $z=36''$  and  $z=66''$ .



**FIGURE 3.** Focused angular profiles of the 35kHz T(m,1) mode group at  $z=114''$  in a 12'' scheduled 40s steel pipe. The angular profiles are: (a) analytical calculation results for a pipe without a weld, (b) FEM simulation results for a pipe without a weld, (c) FEM simulation results for a pipe with a weld at  $z=66''$ , and (d) FEM simulation results for a pipe with two welds at  $z=36''$  and  $z=66''$ .

## EXPERIMENTAL VERIFICATION

In order to verify the FEM simulation results, a 12'' schedule 40s steel pipe was examined at the Battelle Institute in Ohio. The pipeline test facility employed a commercial multi-channel low frequency guided wave generation system, Teletest<sup>®</sup>. The pipe contained deliberately machined defects, a calibration groove and an austenitic stainless steel weld, as seen in Figure 4. In these experiments, a new drilled round bottom hole destructive experiment was monitored by ultrasonic guided wave inspection with torsional guided waves as the hole was increased in depth (Figure 4). The inspections were carried out with the hole at four different sizes: 1) depth = 0.130'', diameter = 0.78'', and CSA  $\approx$  0.37%; 2) depth = 0.225'', diameter = 0.78'', and CSA  $\approx$  0.64%; and 3) depth = 0.280'', diameter = 0.78'', and CSA  $\approx$  0.8%. The inspection results by applying axisymmetric excitations and the phased array focusing technique are shown in Figures 5 and 6. Although the defect was not found by the axisymmetrically loaded waves, as can be seen in Figure 5, the focusing technique made the hole detectable when its CSA was  $\geq$  0.64%.

These experiment results showed that the ultrasonic energy was indeed focused at the defect location. Hence, focusing beyond a weld can be easily controlled by applying the input time delays and amplitude factors obtained by the traditional analytical calculations. In addition, these experiments proved that the focusing technique could enhance detection potential of the guided waves. Usually, over the low frequency range 20kHz  $\sim$  120kHz, the smallest size defect that could be definitely detected by utilizing axisymmetric excitations was 3%  $\sim$  9%. By the employing the focusing technique, the smallest detectable size can be reduced to 1%  $\sim$  3%, or even smaller.

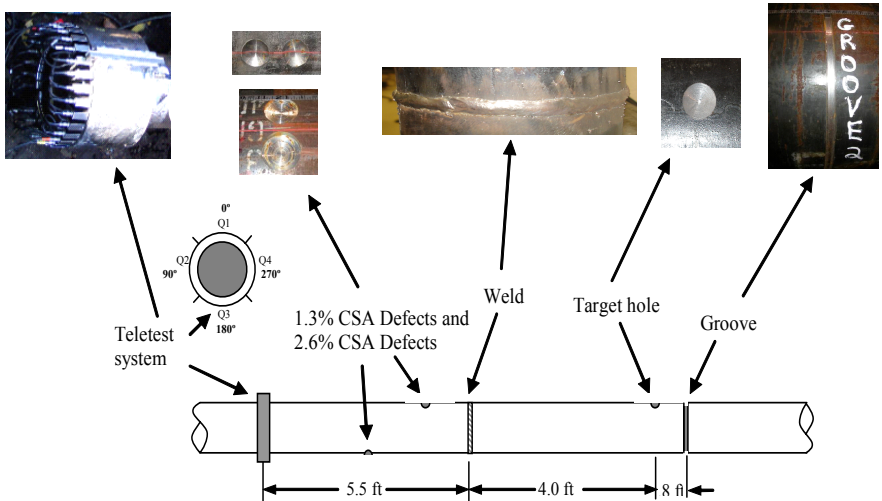


FIGURE 4. Scheme of the experiment setup for low-frequency focusing beyond a weld and 2 small defects in a 12" schedule 40s pipe.

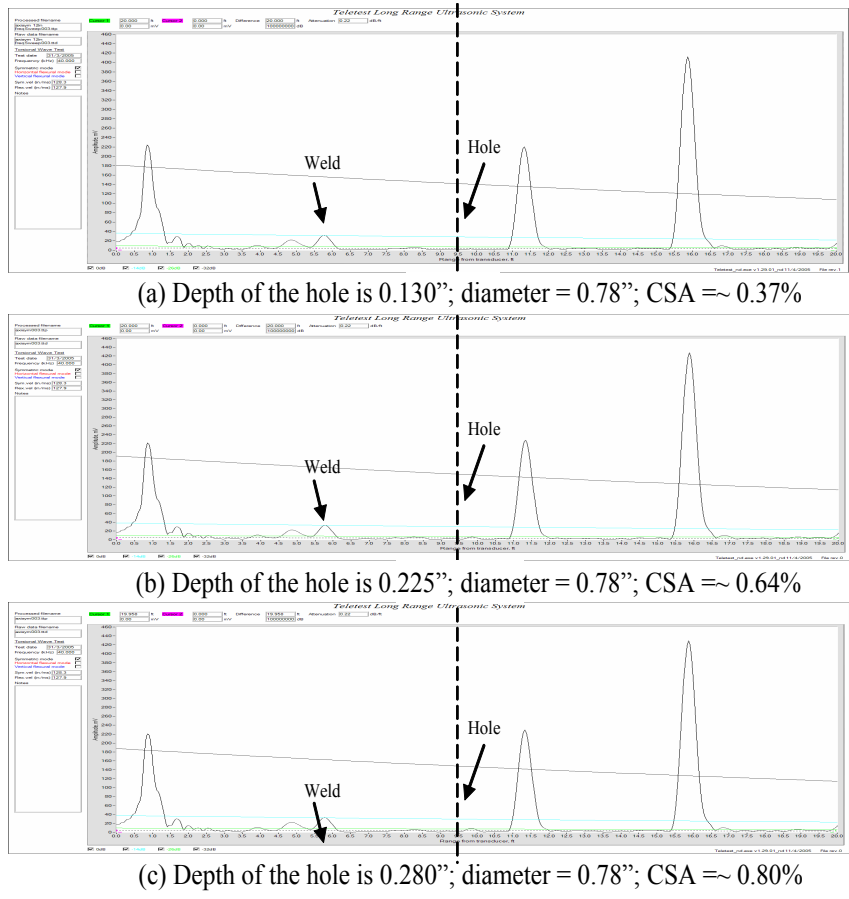
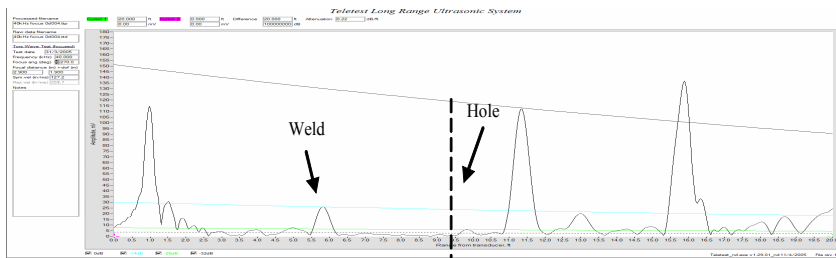
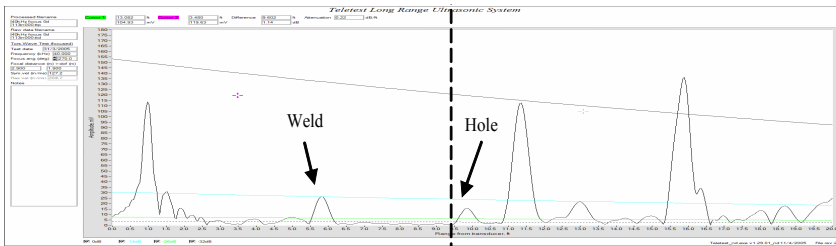


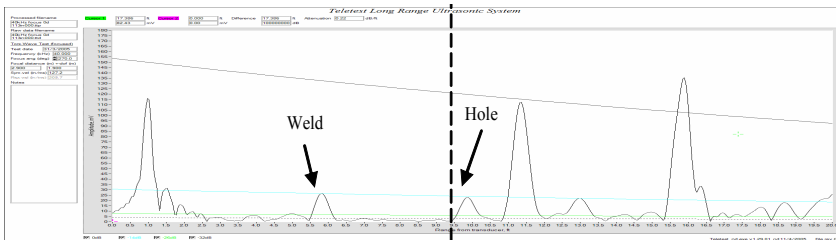
FIGURE 5. Axisymmetric inspection results by using the 35kHz T(m,1) group to detect a growing hole with different sizes. The dashed line shows the start of the hole, which is located at 114" from the transducers. No clearly visible echo from the hole was found.



(a) Depth of the hole is 0.130"; diameter = 0.78"; CSA  $\approx$  0.37%



(b) Depth of the hole is 0.225"; diameter = 0.78"; CSA  $\approx$  0.64%



(c) Depth of the hole is 0.280"; diameter = 0.78"; CSA  $\approx$  0.80%

**FIGURE 6.** By focusing the 35kHz T(m,1) group at the growing hole, the inspection results were significantly improved. The dashed line shows the start of the hole, which is located at 114" from the transducers.

## CONCLUDING REMARKS

The potential of guided wave focusing beyond anisotropic welds in pipelines was studied. Phased array focusing in pipes was successfully simulated by using a 3D FEM. In addition, experiments were carried out to verify the numerical calculations. Both the numerical simulations and the experiments showed that focusing beyond several austenitic transversely isotropic welds was feasible. The input parameters for focusing in an isotropic pipe obtained by analytical computations are still practical to achieve focusing in a tubular elastic isotropic structure with several transversely isotropic welds.

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