

Ultrasonic guided waves reflection from simple dent in pipe for defect rate estimation and parameters determination of axisymmetric wave generation source

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ABSTRACT

In this paper, the reflection of ultrasonic guided waves from simple dent in pipes has been investigated using finite element method and the relationship between reflection coefficient of these waves and deformation rate has been determined. Also, the effect of the parameters of wave generation source on the generated wave field has been investigated using normal modes expansion method. At first, ultrasonic guided waves propagation has been studied in an intact pipe to obtain multiple modes using of displacement potential method. The characteristic equation has been solved using a matlab code in order to draw the dispersion curves of phase and group velocities in different frequencies for longitudinal modes, and it is observed that mode L(0,2) is a suitable mode for inspection in a range of frequency 200-300 kHz. The single sided dent is created in pipe using a plasticity analysis with the aid of finite element simulation and then L(0,2) mode is generated in pipe. By Investigation of the reflection of this mode from dent, the relationship between reflection coefficient and deformation rate is specified and it has been observed that this relationship is almost linear by curve fitting. Also, it has been observed in case of partial loading by wave generation source that is a transducer with a specified axial length and circumferential coverage angle, a combination of different modes such as L(0,2) mode is generated in pipe, if using a axisymmetric wave generation source including 8 segments 45 degree, only L(0,2) symmetric mode is generated.

1. Introduction

Ultrasonic guided waves are used in the processes of inspection in structures like pipes and plates to locate defects such as crack, perforation, corrosion and dent. Alleyne and cawley examined the effect of different discontinuities on the propagation of lamb waves in pipes and they also studied the reflection of these waves from the discontinuities of these surfaces [1]. Alleyne et.al investigated wave reflections and mode conversion from the surface of the circumferential notches in the pipes by applying empirical methods and finite element methods [2, 3]. These waves were used long range inspection of chemical plant pipes to identify corrosion [4]. Non-destructive ultrasound guided testing is used in today's highly sensitive industries such as aircraft construction, maintenance, nuclear power plants, pipelines fluid transfer.

This method is also applied, in the assessment of underwater pipes and offshore pipelines [5, 6]. There are sure obstacles in applying this method, of which we can refer to the existence and propagation of different modes at different frequencies. Proper mode control of guided waves has many benefits in terms of sensitivity to specific

damages in the structures to environmental variables, and also to infiltration power and others factors in the process of inspection by guided waves [7]. Ultrasonic guided waves are applied to find dents in the pipe and determine deformation rate [8]. Ultrasonic guided waves are propagated along the thickness of the pipe and its length and after reaching the dent, the waves collide with it and part of the of the waves energy is reflected and the other part passes the dents. Reflection coefficient is expressed as the ratio of the reflected wave amplitude to the submitted wave amplitude. By combining the characteristics obtained from wave reflection by dent, we will be able to analyze the relationship between the reflected wave coefficients and the rate of change.

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In this study, at first the dispersion curves of phase and group velocities in different frequencies in an intact pipe are obtained and the most appropriate mode is selected for the inspection process. Then, the relationship between the wave reflection coefficient of and the rate of the deformation caused by simple dents within the pipe is determined through simulating finite element in abacus software. Finally, a resource of wave generation with $2L$ axial length and $2\alpha_0$ segment angle is considered and the effects of parameters of this source on the wave field generated by the method of normal modes expansion are examined and it is determined what modes are produced in the pipe and the range of coefficients of the modes produced is calculated using the written program .Wave generation source parameters are determined using the normal modes expansion method for generating the most appropriate mode.

2. The dispersion curves of ultrasonic guided waves

By solving characteristic equation of ultrasonic guided waves in the pipes, the characteristics of axisymmetric longitudinal mode, axisymmetric torsional mode and non-axisymmetric flexural mode in the pipe including phase velocity and group velocity obtained based on frequency.

Figure 1 shows the dispersion curves of phase velocity and group velocity of axisymmetric longitudinal modes for an aluminum pipe with geometrical and the mechanical characteristics mentioned in Table 1, these curves are plotted in the frequency range of 0-5 MHz for the first six modes.

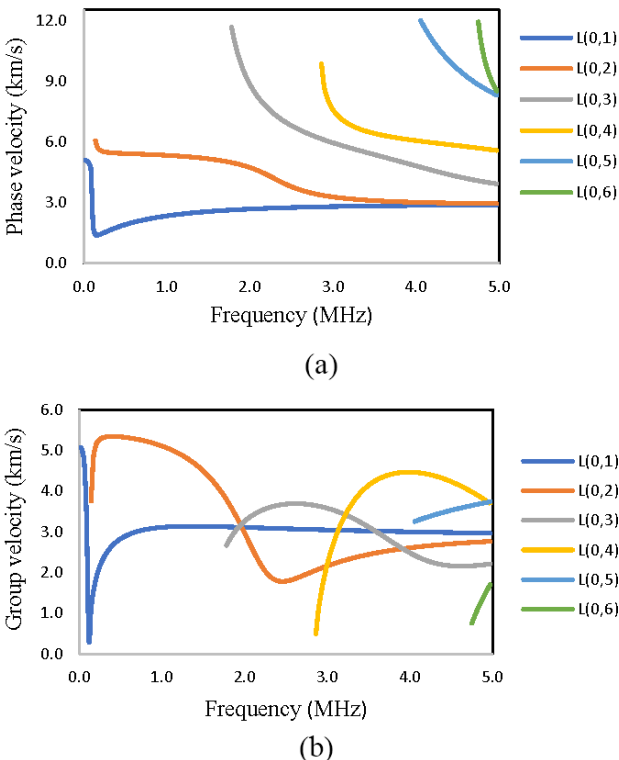


Figure 1. Dispersion curves of axisymmetric longitudinal waves for an aluminum pipe (a) phase velocity (b) group velocity.

By examining the curves of longitudinal waves, the most appropriate longitudinal mode for the inspection of the aluminum pipe is $L(0,2)$. This mode is applied in the simulation of finite element in order to find the relationship between the reflection

coefficient and the rate of pipe recess. Among the reasons for choosing this mode the followings are accounted:

- (1) Bandwidth of this mode is constant in the frequency range 200-300 kHz. It does not change and is suitable for pipe inspection.
- (2) The group velocity of this mode to 2 MHz frequency is higher than other modes and the fastest mode is in this frequency range and the signal reaches faster to the receiver than other modes and detaches faster than other modes.
- (3) The production of this mode is easier than others and when produced non-axisymmetric flexural modes is not produced.

Table 1: Geometrical and Mechanical properties of

Poisson ratio	Yang module (Gpa)	Density (kg/m ³)	length (mm)	Outer diameter (mm)	Thickness (mm)
0.33	70	2700	1250	16	1

3. Plastic modeling of pipe dent

To produce an appropriate inspection mode in a pipe with simple dent, first a plastic analysis is used to simulate one-way dent. Figure 2 shows the geometrical position of the dent in the pipe. In order to simulate this dent, it is necessary to profile the pipe sections at sufficient points around the collapsed area. For this purpose, the simulation of finite element is used. Numerous models are applied for plastic analysis of different solids material have been proposed that are tailored to the reaction of the material in the deformation state, is considered to be the most appropriate method. The depth of the dents is considered to be largest reduction in pipe diameter to that of a healthy pipe.

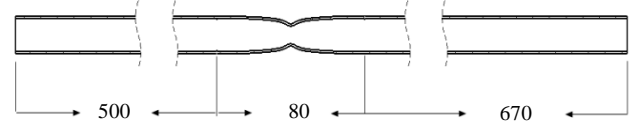


Figure 2. Aluminum pipe and the distance of the dent from its two ends (the dimensions are in mm)

The considered dent is generated by applying controlled displacement to the steel rigid bar with 6 mm diameter and 20 mm length that is perpendicular to the pipe axis. From a rubber support with 100 mm length, 80 mm height, 200 mm depth, 0.055 GPa elastic modulus, 0.45 Poisson's ratio and 1000 kg/m³ density have been used [9]. The coefficient of friction for the contact surfaces between the pipe and the support is 0.6 and between the pipe surfaces and the steel rod is considered 0.45 [10]. To reduce the analysis time, for one-sided dent, one quarter of the pipe middle part where the dent is simulated is considered (Figure 3).

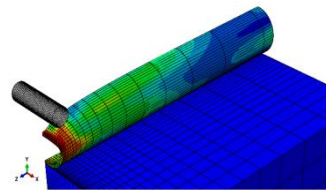


Figure 3. Plastic simulation of simple dent in aluminum pipe.

The element used in this analysis is a three-dimensional hexahedral element with 8 nodes in every its corner is intended. 60 elements along the periphery and 3 elements is in line with the

thickness of the pipe. Because by moving away from the collapsed area, the body is changed to a lesser extent so there is no need for fine grading along the axial alignment. Aluminum among those types of materials that its strain rates is high so the most suitable plastic model for it is the Johnson-Cook. The results of plastic simulation of dent are shown in Table 2. The parameters in this table are those needed in order to plane the collapsed part of the pipe, and has been compared with the experimental results [8]. It has been observed that the maximum error in the plastic simulation of unilateral dent area is 6%.

Table 2. The values obtained for the minimum and maximum outer diameter of the pipe.

No.	Depth of Dent (mm)	Max. Outer Diameter (mm)	Min. Outer Diameter (mm)
1	0	16	16
2	1.6	14.40	16.43
3	2.3	13.70	16.75
4	2.8	13.20	17.08
5	3.8	12.21	17.85
6	4.3	11.70	18.26
7	5.2	10.80	18.96
8	5.9	10.11	19.50

4. Finite element simulation of ultrasonic guided waves generation in pipes

Finite element analysis is one of the most powerful and efficient computational tools for studying wave mechanics in structures. The requirement for successful nondestructive testing is to produce single modes in the non-scattered frequency range so that no other modes are produced [11]. For this purpose, the axisymmetric mode L(0,2) would be produced by simultaneously excitation the nodes which are located at the end of the pipe at the frequency of 240 kHz and ne released along the cylindrical axis. To analyze the ultrasound-guided waves, considerable attention should be paid to the number of elements per wavelength of the under-studied modes in longitudinal, radial, and environmental directions. For the aforementioned aluminum pipe, four surfaces are considered as boundary surfaces. The outer and inner surfaces of the pipe which are adjacent to the air and two primary and end surfaces which are free on one side and bound to the other on the basis of the wave excitation function. Since air is not capable of bear the compressive and shear pressures, therefore; it can be assumed that the pipe is in a vacuum environment, hence no pressure is exerted on its inner and outer surfaces. At the left end of the pipe, where the audio transmitters are located, the transmitter’s effect can be applied by force or displacement. Since in this research, L(0,2) has been selected from the available modes, then to produce the desired mode, particles on the left end of the pipe must be excited simultaneously [12]. The stimulation function used to produce L(2,0) is the tone burst function with 10 cycles and frequency of 240 kHz. Figure 4 shows the curve of this wave function.

Since wave structures may vary dramatically along the thickness (radial direction in a cylinder), usually four or five nodes in thickness are required, in the finite element simulation, a three-dimensional hexahedral linear element with 8 nodes per corner (C3D8R) is used. The following points are considered in

order to determine the minimum number of elements along the axis [13]:

According to Eq. 1, the maximum length of each element must be less than one tenth of the minimum wavelength [14].

$$\Delta L_{max} \leq \frac{\lambda_{min}}{10} \tag{1}$$

In Eq. 1, λ_{min} represents the wavelength, ΔL_{max} represents the maximum wavelengths of the element. The time step must be chosen according to Eq. 2 in which ΔL_{min} indicates the minimum element length, and C_{max} is the fastest speed which can be found in the intended object.

$$t \leq \frac{\Delta L_{min}}{C_{max}} \tag{2}$$

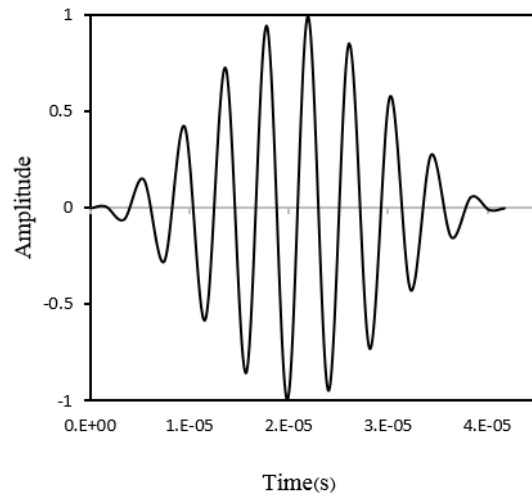


Figure 4. Tone burst function with 10 cycles and frequency of 240 kHz.

L(0,2) mode phase velocity has been obtained by using finite element simulation in different elements to wavelength ratios and its curve is plotted in Figure 5. As you can see in this curve, by increasing the number of elements to more than 21 elements in the wavelength, there is no considerable change in the mode phase velocity. The estimated velocity value for 21 elements to wavelength is 5230 m/s. Compared to analytical method, the error is 0.52%.

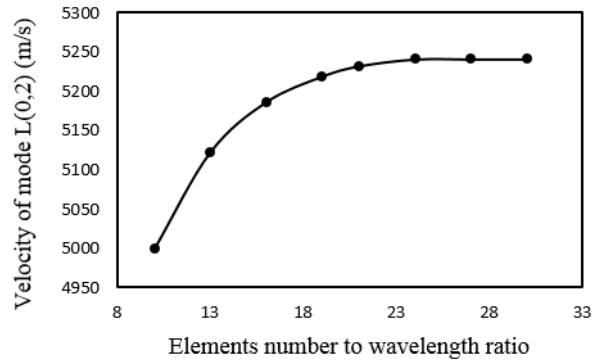


Figure 5. Estimated L (0,2) mode velocity based on finite element analysis for different elements to wavelength ratio.

By examining the obtained characteristics from the wave reflection of the dents, we can determine the equation between the wave reflection coefficient and the deformation rate related to one-way damage.

Reflection Coefficient	Deformation rate (%)	Depth of Dent (mm)
0	0	0
4.5	7.67	1.6
6.4	10.12	2.3
8.5	13.65	2.8
11.2	18.90	3.8
12.4	21.84	4.3
15	26.93	5.2
16.5	31.73	5.9

Figure 6 represents the L(0,2) mode before reaching the dent, As it is shown in the figure; the axial symmetry associated with particle displacement is well apparent. Figure 7 also shows the crossed and reflected L (0,2) mode.

5. Finite element results

The main purpose of the finite element simulation is to investigate the equation between reflected wave signals from the dent and the geometric components of the dent damage. In order to define a quantitative component to correlate the maximum and the lowest diameter of the collapsed region of the pipe, δ has been used which represents the deformation rate obtained from the Eq. 3. L(0,2) mode is created by the tone burst excitation function with 10 cycles to one end of the pipe and 540 mm distance from dent and reflected wave amplitude due to collision with dent is obtained. Based on what we can see in Table 3; wave reflection coefficient calculated in terms of deformation rate and depth of dent. It has been compared with the values obtained from the experimental method [8]. This comparison is shown for one-way dent in Figure 8.

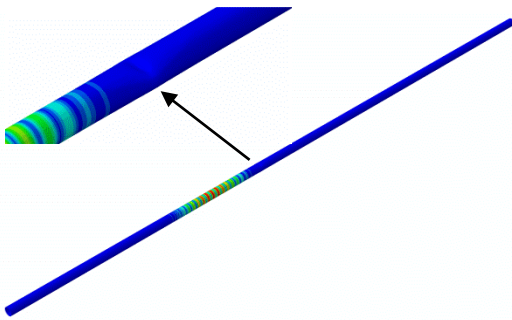


Figure 6. transmitted L(0,2) mode, before reaching the dent.

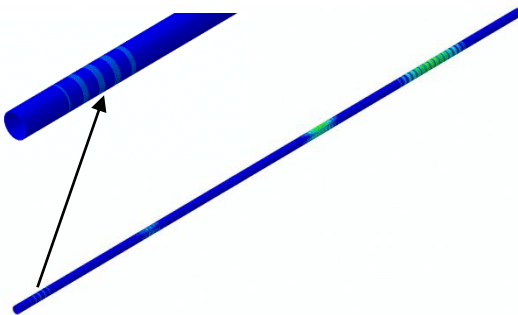


Figure 7. Reflected L(0,2) mode by the dent.

$$\delta = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \times 100\% \quad (3)$$

Table 3. Reflection coefficient obtained from FEA corresponding to deformation rate.

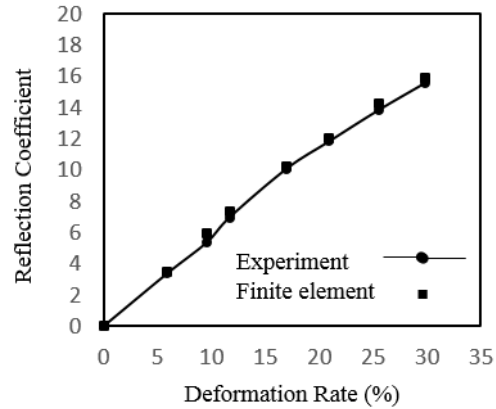


Figure 8. The wave reflection coefficient curve of one-way dent in terms of deformation rate.

6. Influence of non-axisymmetric wave generator source parameters

Influence of wave source parameters on the generated wave field was investigated for the first time using normal mode expansion (NME) method, and the amplitude ratio of generated modes in a specific excitation condition is calculated in the specified frequency [15, 16]. By excitation the pipe by a wave generating source, different modes will be produced in it, and the wave field produced in the pipe is equal to the set of displacements caused by the generated modes. In the previous sections, it has been shown that L(0,2) mode is an appropriate mode to inspect the pipe in the frequency range 200 to 300 kHz. The relation between the wave reflection coefficient and the deformation rate in the pipe has been determined. Now the question is how to produce L(0,2) mode in aluminum pipe? The normal mode expansion method states that if the pipe is excited at a specific frequency a combination of different modes is produced in the pipe.

6.1. Normal modes expansion method

The number of modes propagated in a hollow cylinder or pipe is infinite. Each of these values is the eigenvalues and the eigenvectors of the specific characteristics or dispersion equation. Mathematically, these modes are orthogonal to each other; these modes are known as normal modes. Normal modes expansion method was used to obtain the generated wave field based on the number of infinite normal modes used in hollow cylinders or pipes [15]. The overall displacement field of wave \vec{V} can be expressed as the sum of all normal modes:

$$\vec{V}e^{i\omega t} = \sum_{n,m} A_m^n \vec{V}_m^n e^{i\omega t} \quad (4)$$

Where A_m^n denotes amplitude and \vec{V}_m^n shows wave structure of m^{th} mode and n^{th} circumferential order.

Displacement of particle \vec{V}_m^n is dependent on angular and radial axes in hollow cylinder or pipe, and from Eq. 5 in terms of three components of wave field in directions \hat{e}_r , \hat{e}_θ and \hat{e}_z will be obtained. These three directions are shown in Figure 9.

$$\vec{V}_m^n(r, \theta) e^{i(\omega t - k_m^n z)} = \{U_{mr}^n(r) \Theta_r^n(n\theta) \hat{e}_r + U_{m\theta}^n(r) \Theta_\theta^n(n\theta) \hat{e}_\theta + U_{mz}^n(r) \Theta_z^n(n\theta) \hat{e}_z\} e^{i(\omega t - k_m^n z)} \quad (5)$$

where $U(r)$ represents the distribution of radial displacement field, also $\Theta(n\theta)$ indicates the angular distribution of the displacement field which are sinusoidal and cosine functions. Eq. 5 shows the total displacement in terms of three displacement components. Because of the overall displacement \vec{V} is obtained by using Eq. 4, in the next step all values of the amplitude factor A_m^n must be calculated.

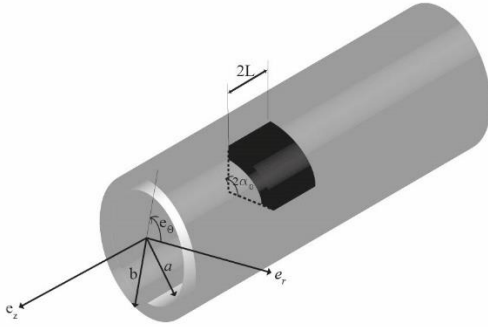


Figure 9. The cylindrical coordinates of a hollow cylinder with partial loading caused by a transducer with axial length of $2L$ and circumferential coverage angle of $2\alpha_0$

6.2. Calculating amplitude factor

Amplitude factor calculation depends on loading conditions. In this section, the partial loading caused by a transducer and its effect on the generated wave field will be investigated. In Figure 9, partial loading by a transducer with axial length of $2L$ and circumferential coverage angle $2\alpha_0$ have been shown. The applied \vec{T} traction on the outer surface of the hollow cylinder or pipe is expressed as Eq. 6:

$$\vec{T} \cdot \hat{e}_r = \begin{cases} -p_1(\theta) p_2(z) & r=b, -\alpha_0 \leq \theta \leq \alpha_0, -L \leq z \leq L \\ 0 & r=b, |\theta| > \alpha_0, |z| > L \end{cases} \quad (6)$$

where $p_1(\theta)$ and $p_2(z)$ represent the loading amplitude function in axial and angular directions, respectively.

The amplitude factor is obtained by using the Eqs. 7 and 8 [15]:

$$A_{+m}^n(z) = \frac{U_{mr}^n}{4P_{mm}^n} \langle \Theta_r^n \cdot p_1(\theta) \rangle \cdot \langle e^{ik_m^n z} \cdot p_2(z) \rangle \quad (7)$$

$$\vec{P}_{mm}^n = \frac{1}{4} \iint (\vec{V}_m^{n*} \cdot \vec{T}_m^n + \vec{V}_m^n \cdot \vec{T}_m^{n*}) \hat{e}_z d\Omega \quad (8)$$

Where the ((+)) sign represents the wave propagation in the +z direction, ((*)) represents the complex conjugate operator, and (($\langle \rangle$)) indicates the inner product. \vec{P}_{mm}^n indicates the penetration power for the m^{th} mode and n^{th} circumferential order [17], also Ω shows the cross section. Using Eq. 7, it can be seen that the amplitude factor of a pure mode can be increased by applying loading function $p_1(\theta)$ and Θ_r^n sinusoidal function. A sample calculation for the Amplitude factor is performed as shown in Figure 10. The calculations were performed for L(0,2) to L(n,2)

modes generated with an 45 degree circumferential loading at 240 kHz for an aluminum pipe with an outer diameter of 16 mm and a thickness of 1 mm. These calculations are performed for the first ten modes and can be performed for a greater number.

As it is shown in Figure 10; ultrasonic guided waves generation by a wave generator with a specific circumferential length and angle will lead to a combination of different modes production, including L(0,2) in a pipe. It is very difficult to generate a pure mode in the pipe. The wave source used is a non-axisymmetric wave source and lead to different modes production in the pipe wall, an axisymmetric wave generating source consisting of 8 segments of 45 degree, no more non-axisymmetric modes L(n,2) will on the pipe wall and axisymmetric modes L(0,2) will only be produced.

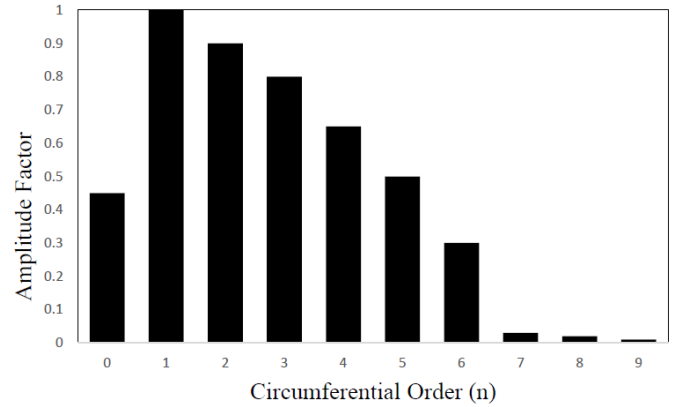


Figure 10. The amplitude factors of L(0,2) to L(n,2) modes generated with an 45 degree circumferential loading at 240 kHz for an aluminum pipe with an outer diameter of 16 mm and a thickness of 1 mm.

7. Conclusion

In this paper, the reflection of ultrasonic guided waves from simple dent in aluminum pipe with different depths were investigated. The geometric characteristics of the unilateral dents are analyzed and also the geometrical characteristics of each depth were determined. The quantitative relationship between the geometric characteristics of the dent and the reflected wave amplitude from dent was obtained, by examining the impact of geometric characteristics of the indentation on reflected signals. In this study, it was observed that the reflection of mode L(0,2) is more intense in the deeper part of the pipe. It was also observed that time of mode L(0,2) transformation in the dent area, specifies the distance of the pipe. A quantitative characteristic called the deformation rate has been defined based on the maximum and the minimum outer diameter of the pipe in the dent area to evaluate the impact of the dent on the wave's reflection factor. In order to determine the rate deformation corresponding to one-way dents, it was shown that the reflectance mode coefficient, L(0,2) is almost a linear function in terms of the deformation rate. Also, the influence of wave generation source parameters, including the source length and the circumferential angle was evaluated on the generated wave field. It was observed that in case of ultrasonic guided waves generation by a wave generation source with a specific length and circumferential angle, the combination of different modes including the L(0,2) mode will be produced in the pipe and the possibility of producing a pure mode in the pipe is impossible. Just in case that a axisymmetric wave generation source which contains 8 segments of 45 degree is used, other non-

axisymmetric modes $L(n,2)$ will not be produced in the pipe wall and only the axisymmetric mode $L(0,2)$ is produced.

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