MECHANISM OF DETECTION OF DISCONTINUITIES IN PIPELINES BY ULTRASONIC GUIDES WAVES

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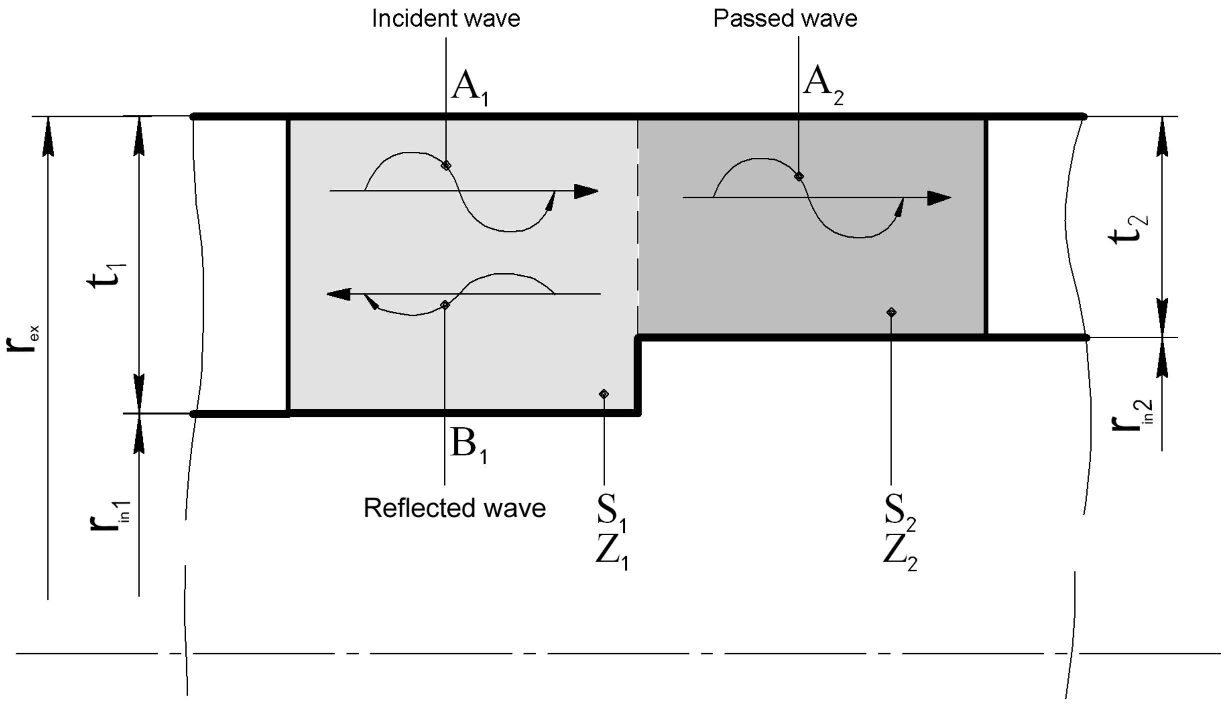
The paper deals with the features of detection of discontinuities in welded pipelines, with which low-frequency guided waves of longitudinal and torsional modes interact during their propagation in the form of a circular wave through the pipe cross-section. Extended welded pipelines are characterized by the presence of various discontinuities in them, related to the change of material density and/or cross-section of pipe walls on their joint boundary and/or along the pipe length. The main pipeline discontinuities are defects of metal loss in pipe section, resulting from corrosion damage and erosion wear of pipe wall. Such defects leading to pipe wall thinning, are the interfaces, which influence the transmission of ultrasonic low-frequency guided wave during its propagation along the pipeline as an extended wave guide. Influence of pipe wall defects as interfaces on ultrasonic wave propagation is exactly what forms the base for the mechanism of defect detection by low-frequency guided waves.

Interaction of guided wave with pipe defects. Interaction of guided wave with pipeline defects is based on the principle of reflection and propagation of an incident ultrasonic wave on each interface, which is due to a change of pipe wall cross-section. On each interface the incident wave is divided into the reflected and passed wave.

Let us analyze in the general form the processes of reflection and passing of guided waves on the transition boundary of one wave guide of section S_1 to the second wave guide of section S_2. We will regard the boundary of waveguide transition as an inseparable absolutely rigid contact of two pipes with different material constants ρ_1, E_1 and ρ_2, E_2 for guided mode of the longitudinal wave. Principle of reflection and passing of guided waves on the boundary of wave guides of different cross-sections is shown on a pipeline fragment with different inner diameters of pipes, which is given in the Figure, where t_1, r_{in1} and t_2, r_{in2} are the wall thicknesses and inner radii of the first and second pipe, respectively; r_{out} is the pipe outer radius.



Principle of reflection and passage of guided waves on the boundary of pipe section change

If a square-wave pulse with sinusoidal filling of the required frequency is excited at one end of the pipeline, then ultrasonic wave of amplitude A_1 will propagate through pipe wall thickness along the pipeline longitudinal axis. Propagating along waveguide section with cross-sectional area S_1 incident wave of amplitude A_1 comes across another waveguide, the cross-sectional area of which is equal to S_2. The incident wave is transformed into a reflected wave, amplitude B_1 of which depends on the degree of change of pipe cross-section, and into passed wave with amplitude A_2, which propagates further along the pipe section.

As reflected wave formation occurs in a section of change of pipe cross-sectional area, consideration of the processes of acoustic wave propagation in waveguides is performed using the concept of mechanical impedance *Z*, dependent both on waveguide parameters (its cross-sectional area *S*), and on the medium properties, namely velocity of sound *C* and density ρ. Mechanical impedance is an important parameter of an extended pipeline medium. In pipe zones without defects, the controlled pipeline has finite mechanical impedance. Change of mechanical impedance is related both to a change of pipe cross-sectional area due to its corrosion damage and erosion wear, and to a change of wave impedance of welded joint medium and its cross-sectional area, because of the presence of various discontinuities. Therefore, mechanical impedance, essentially is a measure of pipe resistance to propagation of guided ultrasonic waves. The Figure shows the simplest case of transition from the first pipe with mechanical impedance $Z_1 = \rho_1 C_1 S_1$ to a sufficiently long pipe with mechanical impedance $Z_2 = \rho_2 C_2 S_2$.

Coefficients of reflection *R* and passage *W* of guided wave from the jump of mechanical impedance on the interface of the two media are found from the following expressions:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}; \qquad W = \frac{2Z_2}{Z_2 + Z_1}. \qquad (1)$$

Product of ρC in expressions for mechanical impedance is the specific acoustic impedance of the medium and represents the wave impedance of the medium. Wave impedance characterizes the reflecting properties of the medium and determines the conditions of sound reflection and passage on the boundary of the two media. If wave resistances of the media are equal, the coefficients of reflection and passage of the guided wave will depend on the change of the pipe wall cross-section.

Proceeding from that, according to the Figure, coefficients of reflection *R* and passage *W* of low-frequency ultrasonic wave from the jump of mechanical impedance of pipe medium will be determined by the following expressions:

$$R = \frac{S_2 - S_1}{S_2 + S_1}; \qquad W = \frac{2S_2}{S_2 + S_1}. \qquad (2)$$

As guided wave propagation occurs in the direction of reduction of pipe cross-section ($S_2 < S_1$), a reversal of the phase of the reflected wave relative to the incident wave is observed. Passed wave has the same phase as the incident wave. Depending on values of S_2 and S_1, reflection coefficient *R* will have a negative or positive value. At positive *R* the phase of the reflected signal does not change. Frequencies of the incident and reflected waves are equal in all the cases, this greatly facilitating solution of the problem of guided wave reflection.

Assessment of reflected signal amplitude. Let us assess the dependence of the amplitudes of the reflected and passed wave on the degree of change of the pipe cross-sectional area, because of the presence of defects along the pipe length. On each interface the incident wave will split into one reflected and one passed wave, which results in these waves forming a sequence of completely separated and independent from each other individual pulses. Each passed wave will be smaller than the incident wave by amplitude after the interface. In the section of the last defect along the pipe length incident wave of amplitude A_{in} is transformed into reflected wave of amplitude B_{in} and passed wave of amplitude A_{end}, which is reflected from the end of pipe with amplitude B_{end}. In the absence of attenuation of a low-frequency guided wave in the pipeline final section, amplitudes of passed wave A_{end} and reflected wave B_{end} will be equal. Therefore, the following dependence of the amplitudes of the passed and reflected from defect waves will be in place in the entire tested pipeline section:

$$\begin{aligned} B_1 &= A_1 - A_2; \\ B_2 &= A_2 - A_3; \\ &\ldots\ldots\ldots\ldots\ldots\ldots \\ B_n &= A_n - A_{\hat{e}}. \end{aligned} \quad (3)$$

Amplitudes of each of the pulses of the reflected and passed waves can be calculated, if we apply formulas (2) to each individual process of guided wave reflection and passage on the interface. Sound pressure of the pulse sequence will decrease each time, as a result of the next splitting.

Taking into account expressions (2) for determination of coefficients of reflection R and passage W of the guided wave on the boundary of the change of pipe wall cross-section, amplitudes of reflected B_1 and passed A_2 waves will be determined by formulas of the following form:

$$B_1 = R \cdot A_1 = \frac{S_2 - S_1}{S_2 + S_1} A_1, \quad (4)$$

$$A_2 = W \cdot A_1 = \frac{2S_2}{S_2 + S_1} A_1. \quad (5)$$

From expression (4) it is seen that the value of reflected wave amplitude is proportional to the difference of areas $S_2 - S_1$, i.e. depends on the dimensions of corroded cross-sectional area of the pipe wall. This means that the low-frequency guided wave is sensitive to metal losses in pipe cross-section. From expression (4) it also follows that the coefficient of reflection by amplitude, due to a jump of pipe cross-section because of the presence of a defect, is much smaller than the cross-sectional ratio S_2/S_1. Therefore, the guided wave propagates further along the pipe and only its small part is reflected from the jump of the pipe cross-section.

Assuming that the cross-sections in the defect location differ only by two times, i.e. $S_2 = 1/2S_1$, reflected wave amplitude B_1 will be equal to:

$$B_1 = \frac{S_2 - S_1}{S_2 + S_1} A_1 = -\frac{S_2}{3S_2} A_1 = -\frac{1}{3} A_1. \quad (6)$$

In this case, the amplitude of passed wave A_2 will be equal to:

$$A_2 = \frac{2S_2}{S_2 + S_1} A_1 = \frac{2S_2}{3S_2} A_1 = \frac{2}{3} A_1. \tag{7}$$

Let us assess the faction of excited wave energy which is reflected at section ratio $S_2 = 1/2S_1$. It is known [1] that the coefficient of reflection R_e of incident flat sound wave on the boundary of cross-sectional change of an object with the same material constants evaluated in terms of energy, is equal to:

$$R_{ý} = \left(\frac{S_2 - S_1}{S_2 + S_1} \right)^2. \tag{8}$$

In the general case it means that only a small fraction of sound wave energy is reflected back from the defect, whereas a considerable part of energy propagates further along the pipe. For ratios of pipe sections $S_2 = 1/2S_1$ from expression (6) value of sound wave reflected energy will be equal to:

$$\left(\frac{B_1}{A_1} \right)^2 = \left(\frac{1}{3} \right)^2 = \frac{1}{9}. \tag{9}$$

From expression (9) it follows that if the sections of a sound and defective pipe differ by two times, only 1/9 of incident energy is reflected back. According to [2], the law of conservation of energy is satisfied. This law states that the difference of energies of the incident and reflected wave should be equal to the passed wave energy. As energy density is proportional to the square of amplitude, the following relationship is fulfilled:

$$S_1 \left(A_1^2 - B_1^2 \right) = A_2^2 S_2. \tag{10}$$

Although only a small fraction of sound wave energy is reflected back from the defects, the reflected echo-signal amplitude is the main parameter, which forms the base of the mechanism of detection of defects of corrosion damage and erosion wear of pipe wall, as the value of echo-signal amplitude corresponds to the degree of pipe cross-section variation.

References:

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2. Skuchik E. Fundamentals of acoustics. Transl. from English. – M.: Mir, 1976, v.1. – 520 p.