METHOD AND TECHNOLOGY OF DIAGNOSTICS OF PIPELINE SYSTEMS BY GUIDED LOW-FREQUENCY ULTRASONIC WAVES

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Pipeline systems (pipelines) are one of the most common types of welded structures and they are widely applied in various industries in different countries of the world. They are designed for transportation of liquid, gaseous and bulky substances (products) at different pressures and temperatures. Because of their different capacity, pipeline dimensions (diameters) cover a broad range. In general pipelines can be classified as main pipelines, factory process piping, power plant piping, residential and industrial sanitation piping. A common feature for all kinds of pipeline systems is presence of a large number of welded joints, the absolute majority of which are circumferential butt welds.

Continuous monitoring of pipeline technical condition is important for ensuring their performance. Monitoring pipeline technical condition by regular NDT methods is, however, quite complicated, as pipelines are enclosed in insulation under the ground, some pipe sections are raised above the ground, individual sections are immersed in water, are located in sleeves under the railway and other transitions. Therefore, at present diagnostics of extended pipelines mostly has to be based on the concepts and criteria of defectiveness of metal both of the weld, and the pipe, so as to have at least some, even though indirect assessments of the current technical condition of pipeline systems, as a whole.

A significant step forward in development of the methods of monitoring the technical condition of extended pipelines was development of the technology and systems of remote monitoring of extended pipelines by the method of long-range low-frequency ultrasonic testing (LH UT) by guided waves. Such technology of monitoring various-purpose pipelines became the most intensively developed in the middle of 1990s in Great Britain [1], USA [2], and then in Japan [3]. Analysis of the features of propagation of low-frequency ultrasonic guided waves, systems of diagnostics of various purpose pipelines, using various types of transducers for excitation of guided waves of the longitudinal and torsional mode and reception of reflected signals from pipeline discontinuities, is given in [4]. A considerable advantage of this technique over the traditional UT techniques consists in the ability to use it both for in-process inspection of the technical condition of various-purpose pipelines after their mounting by forming the initial defectogram of the pipeline, and for their subsequent monitoring and creation of data base for calculation of pipeline system operation life.

LH UT technique is based on excitation in the monitored extended pipeline of low-frequency ultrasonic oscillations from one point of acoustic array mounting on the pipeline. Acoustic arrays are based on different types of transmitters, namely piezoelectric, magnetostrictive and electromagnetic acoustic transducers. Pipeline system diagnostics is most often performed using acoustic arrays based on piezoelectric transducers, which are used both for excitation of US oscillations in the pipeline, and for reception of the reflected echo-signals. The principle of excitation of LH U waves and their reflection from the discontinuities and the pipe end is given in Fig. 1.

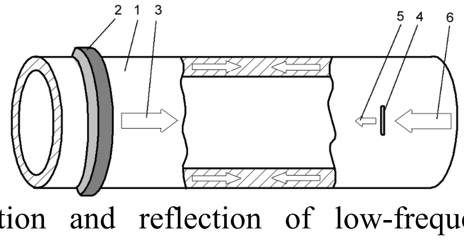
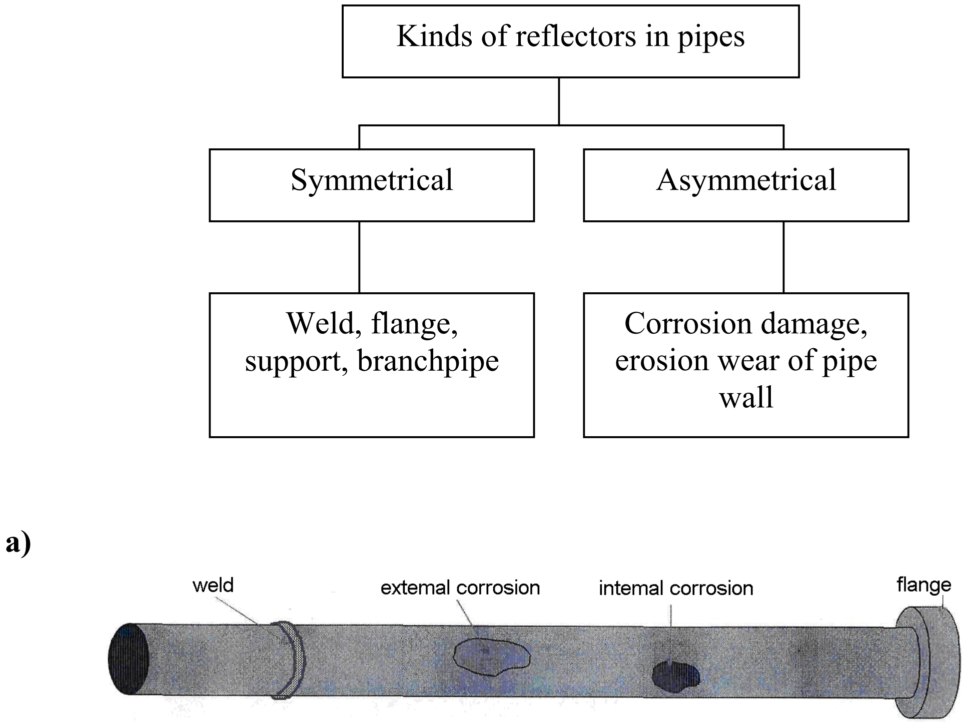


Fig. 1. Principle of excitation and reflection of low-frequency ultrasonic waves from discontinuities and pipe end

During diagnostics of technical condition of pipelines by LF US guided waves acoustic array *2* in the form of a circle of piezoelectric transducers is mounted on pipe *1*. Transducers are uniformly arranged equidistantly to pipe surface with the same step to induce a uniform directional characteristic of excited circular wave *3* of LF US oscillations. When the guided wave runs against any reflector ***4***, created, for instance, by the pipe wall cross-section variation, part of acoustic wave *5* is reflected back to piezoelectric transducers. The rest of the wave travels along the pipe, and then the propagated wave *6* is completely reflected from the pipe end.

A characteristic feature of extended pipelines in long-term operation is presence of various reflectors in them, which form both in pipeline construction and during their operation. Fig. 2 gives the classification of the kinds of reflectors in the pipeline and schematic of their possible location on the pipe.



b)

Fig. 2. Classification of reflector kinds in a pipeline (a) and schematic of their possible location on the pipe (b)

All reflectors in a pipeline can be divided into two kinds: symmetrical and asymmetrical. Symmetrical reflectors include welds, flanges, supports, branchpipes, the location of which on the pipeline is known from the technical documentation. Echo-signals from symmetrical reflectors are important markers for determination of the location of asymmetrical reflectors. Asymmetrical reflectors include defective pipe sections, most often arising from damage of the pipe wall cross-section because of corrosion and erosion wear of pipe wall. Corrosion damage of pipe wall is oriented both along the pipe circumference, and along the pipe longitudinal axis. They may be located both on the inner and outer surfaces. It is, however impossible to identify the actual surface using remote ultrasonic testing. Damage due to erosion wear of pipe wall, is most often oriented along the pipe longitudinal axis and located from the inner surface side. Asymmetrical reflectors can be located in different parts of the pipe. Echo-signals from symmetrical reflectors are used to locate them along the pipe. In the presence of defects in the weld which are due to weld shape distortion and corrosion damage, it will be indentified simultaneously with the weld.

Two wave modes, namely the longitudinal and torsional mode, are mainly used to monitor the technical condition of pipeline systems by LF guided wave UT. An essential feature of these waves is minimum dispersion of their group velocities in certain ranges of ultrasonic wave frequencies. To implement the technologies of extended pipeline monitoring, it is rational to use the symmetrical longitudinal mode of zero order L(0.1) or L(0.2) in the region of minimum velocity dispersion, or nondispersion zero torsional mode T(0.1). Of the longitudinal wave modes the most suitable mode is the high-velocity zero longitudinal mode L(0.2), the velocity of which is independent on frequency in the frequency range above 20 kHz. Torsional waves with zero order T(0.1) mode are characterized by equality of phase and group velocities and have no dispersion. Although guided waves of the torsional mode propagate in the pipe at a lower velocity, they have a higher sensitivity to non-uniformities, compared to the longitudinal wave. However, absence of dispersion and low velocity of the torsional wave allow reducing the dead area and improving the resolution during defect detection in an extended pipeline.

An essential difference of the method of long-range guided wave UT from the traditional UT techniques, is the use of the principle of dry acoustic contact of the transducers with the pipe surface in acoustic arrays, eliminating application of liquid couplants.

At a constant value of the amplitude of exciting signal in the transducer piezoelectric elements the reflected signal amplitude at piezoelectric element output, and, accordingly, transmission coefficient of the testing system, will depend on the constant force of piezoelectric transducer pressing to the pipe surface and degree of roughness of the latter. In each concrete case of pipeline monitoring by guided waves the value of the clamping force should be rated, directed normal to the line of contact of the piezoelectric transducer with the pipe surface and uniformly distributed along the line of contact. When a circular acoustic array is used, these requirements are met due to the design of the clamping down device.

In the general case a pipeline is a waveguide in the form of an infinite elastic medium, designed for transmission of elastic oscillations of a low-frequency guided wave of a certain type from the oscillation source. However, the elastic medium of an extended pipeline will correspond to “waveguide” definition only in the case, if a certain type of oscillations (waves) prevails in it, and the other types have negligibly small values. In addition, it is necessary to ensure transmission of elastic oscillations along an extended pipeline so that no distortions of a plane guided wave developed, and the phenomenon of geometrical dispersion of the velocity of oscillation propagation was absent. For practical elimination of other types of oscillations and ensuring an undistorted transmission of excited elastic oscillations, the nature of wave processes in such a waveguide should correspond to a certain ratio of pipe wall thickness t and working frequency f of the signal of excited low-frequency ultrasonic wave. For pipelines these ratio is selected from the condition $t \times f \leq 1$ mm · MHz. The length of the wave propagating in the pipeline ,$\lambda = C/f$, where C is the sound velocity in it, should be much greater than pipe wall thickness, i.e $\lambda >> t$.

When studying the processes of interaction of guided wave elastic oscillations with pipeline discontinuities, it is necessary to take into account the parameters of its medium as an infinite waveguide. Such pipeline parameters as an acoustic system include specific acoustic impedance z_a and mechanical impedance Z [5].

Specific acoustic impedance z_a is an important parameter of the system with distributed constants and represents its medium wave impedance, which is equal to $z_a = \rho C$, where ρ is the medium density. Wave impedance is an important parameter of pipeline medium, as it characterizes the medium reflecting properties and determines the conditions of sound reflection and passage on the boundary of the two media. If wave impedances of the media are equal, the wave passes through the boundary without reflection.

Mechanical impedance Z is the second important parameter of an extended pipeline medium. Mechanical impedance, essentially, shows the degree of pipeline medium resistance to ultrasonic guided wave propagation, which is what leads to appearance of reflected signals from discontinuities in the pipeline.

If we consider any discontinuity in the pipeline as an interphase of two solids with different mechanical impedances of the medium, the coefficients of LF US guided wave reflection and propagation can be determined by the following expressions:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 C_2 S_2 - \rho_1 C_1 S_1}{\rho_2 C_2 S_2 + \rho_1 C_1 S_1}; \quad W = \frac{2Z_2}{Z_2 + Z_1} = \frac{2\rho_2 C_2 S_2}{\rho_2 C_2 S_2 + \rho_1 C_1 S_1},$$

where R, W are the coefficients of LH US wave reflection and propagation, respectively;

Z_1, Z_2 are the mechanical impedances of the defect-free and defective pipe sections, respectively;

ρ_1, C_1, ρ_2, C_2 are the wave resistances of the respective pipe sections;

S_1, S_2 are the cross-sectional areas of the defect-free and defective pipe sections, respectively.

If $Z_2 < Z_1$, the value of reflection coefficient R will be negative, which means a reversal of the reflected wave phase relative to the incident wave. The propagating wave has the same phase as the incident wave.

The main parameter forming the base of development of systems of LF UT with guided waves is the reflected echo-signal amplitude. The reflected echo-signal amplitude, essentially, corresponds to the degree of the change of the pipe cross-sectional area under the impact of corrosion, i.e. it depends on defect size. At increase of defect size, the duration (width) of the echo-signal also increases. Correspondence between the reflected signal amplitude and the degree of the change of the pipe cross-sectional area under the impact of corrosion is the fundamental technological feature of extended pipeline inspection with low-frequency guided waves, which propagate across the pipe wall thickness along its longitudinal axis. Thus, only the respective shape of the received reflected signals can provide valid proof of the presence (absence) of damage. However, accurate determination of damage dimensions, its type, criticality, etc. is almost impossible, even if its location along the pipe length is known. On the other hand, the amplitude of echo-signals reflected from the real defect gives some idea of the depth of pipe wall damage, depending on the change of pipe cross-sectional area. However, this technology does not provide such a resolution as the remaining thickness of pipe wall damaged by the defect, measured in situ.

In pipeline monitoring by low-frequency ultrasonic guided waves, the amplitude of echo-signal reflected from the defect, characterizes the degree of defectiveness D of pipe cross-section. Degree of defectiveness D is determined by the cylindrical section of the pipe in percentage of defect area S_q to the entire cross-sectional area of the pipe, S_p i.e.

$$D = \frac{S_q}{S_p} \cdot 100\%.$$

Information on pipe wall thickness is determined at ultrasonic measurement of thickness. The ultrasonic waves are directed across the thickness normal to pipe axis. Therefore, information about the amplitude of reflected echo-signal of the guided wave does not include the corrosion depth, which, in principle, is the information obtained across the thickness. Corrosion depth characterizes degree H of pipe wall thinning, which is determined as a percentage ratio of corrosion depth H to nominal thickness t of pipe wall, i.e.

$$H = \frac{h}{t} \cdot 100\%.$$

Therefore, there is no direct correlation between the data on defects, derived using guided waves, and data on thinning depth, obtained at measurement of wall thickness. Let us show it in the case of corroded equivalent cross-sectional area of the pipe detected with guided waves. Schematic of corrosion damage of pipe cross-section of equivalent area with different depth from the side of pipe inner surface is given in Fig. 3.

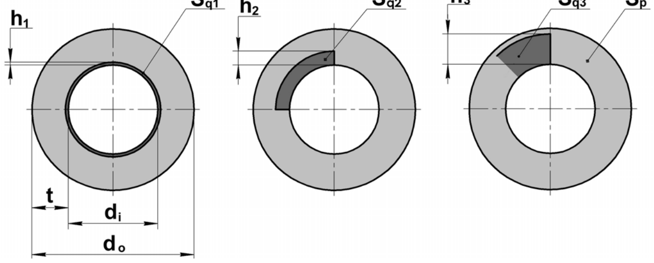


Fig. 3. Schematic of pipe inner surface corrosion damage of equivalent area of different depth.

Let us assume that the area of defective section is $S_{q1} = S_{q2} = S_{q2}$, and the degree of pipe wall defectiveness $D = 9\%$. For a pipe of outer diameter $d_o = 1124$ mm and wall thickness $t = 6$ mm, the depth of wall thinning in the presence of uniform corrosion around the entire inner diameter of the pipe will be $h_1 = 0.54$ mm (Fig. 3, a). Now, if corrosion concentration on ¼ of pipe circumference is assumed (Fig. 3, *b*), the assessed value of thinning depth will be $h_2 = 2.16$ mm. At corrosion concentration on 1/8 of pipe circumference (Fig. 3, c) the value of thinning depth will be $h_3 = 4.32$ mm.

This does not allow stating that there is a direct dependence between the area of pipe cross-sectional damage and depth of wall thinning. In the general case, the guided wave is sensitive to the change of the pipe cross-sectional area in the combination of the depth of wall loss and length along the pipe circumference. Although a deep defect of the same area with a short length around the pipe circumference can generate a greater reflection, the reflected signal amplitude carries general information about the degree of damage of the pipe cross-sectional area, and it is impossible to substantiate the information about the depth of pipe wall loss from this data. Such information can be provided by other physical means of pipe wall measurement, for instance ultrasonic thickness measurement. Fig. 4 gives the schematic of the algorithm of evaluation of the degree of defectiveness and thinning of the wall in pipe cross-section.

Let corrosion damage of the pipe wall be revealed by long-wave ultrasonic flaw detector, and the depth of wall thinning be measured by ultrasonic thickness meter. The reflected echo-signal amplitude, measured in mV, gives an idea of presence of corrosion damage and degree of pipe wall damage. Such an assessment of the degree of pipe wall defectiveness is qualitative. Value of thinning (thickness) of the pipe wall is measured in mm, so that assessment of the degree of pipe wall thinning is quantitative. There is no total correlation between these values, as different physical parameters are measured. Assessment of the depth of thinning by signal amplitude can be performed to a certain extent, if the kind of corrosion is known. However, this is difficult to perform in practice, when initial pipeline inspection is conducted first. Furtheron, such a correlation can be established during monitoring of the pipeline technical condition, as a result of creation of the pattern of corrosion damage development, accumulation and analysis of the actual statistical data on defects using the means of long-range UT by guided waves and local NDT means. This means that in order to solve the problems of pipeline monitoring by low-frequency guided waves, it is necessary to maintain feedback based on the obtained actual statistical data, which may be used to establish a correlation between these data.

Proceeding from the above, we may propose the overall schematic of a complex of methods of diagnostics and non-destructive testing of technical condition of various-purpose pipelines with application of long-range UT by low-frequency guided waves for defect detection, which is given in Fig. 5.

Complete testing of the entire pipeline length is followed by assessment of sections, in which corrosion was detected, by thickness measurement with an ultrasonic thickness meter or other testing techniques (radiographic, eddy current). After that points for continuous observation and monitoring of pipeline technical condition are determined, if required.

The E.O.Paton Electric Welding Institute of the NAS of Ukraine has been developing a technology and technical means of long-range LH guided wave UT of extended pipelines. An experimental welded pipeline 48 m long from 6 m pipes was constructed to study the processes of GW propagation. Pipes of 114 mm outer diameter and 6 mm wall thickness from St.3 steel grade were used in the pipeline. The pipeline is mounted on special supports, insulating it from the environment. During research performance different acoustic arrays based on piezoelectric transducers were created and tested for excitation of a guided wave of the longitudinal and torsional mode. The arrays provide the required force of piezoelectric transducer clamping to the pipe surface to establish a reliable dry contact. To optimize the technology of defect detection in pipes by reflected echo-signal parameters, the method of physical simulation of real defects by mechanical introduction of local discontinuity models in pipes was used. The following was accepted as such discontinuity models: pipe wall thinning of (18x10) size at 3.2 m distance from the point of acoustic array mounting; cut by the pipe circumference of 2.5 mm width; 2.5 mm depth; 0.5 L length, where L is the length of pipe circumference, at the distance of 4.48 m from the point of acoustic array mounting; cut of 2.5 mm width, 2.5 mm depth; 0.3 L length at 14.91 m distance from the point of acoustic array mounting. The working frequency of the excited signals was 19.6 kHz.

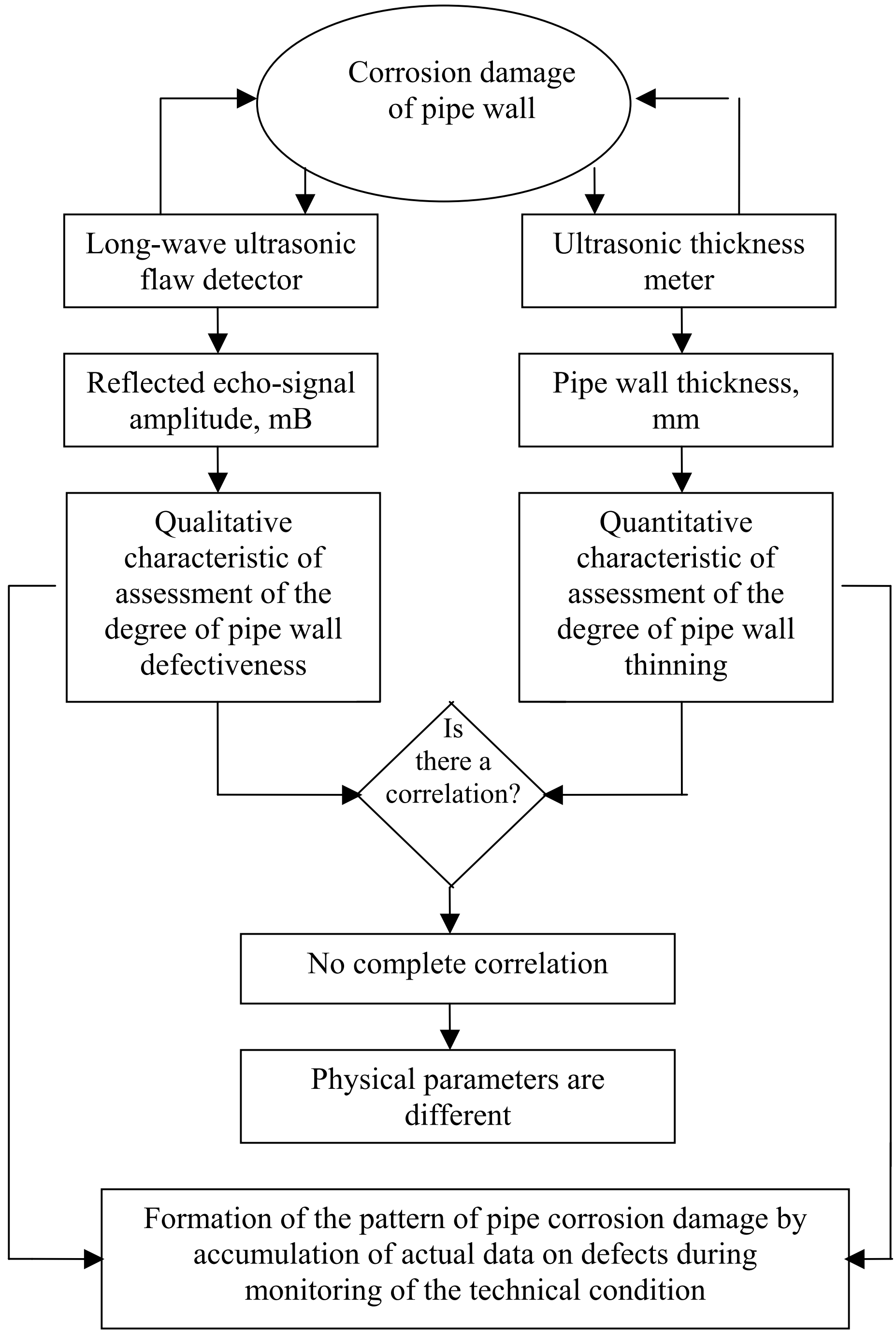


Fig. 4. Algorithm of assessment of the degree of defectiveness and thinning of the pipe cross-section

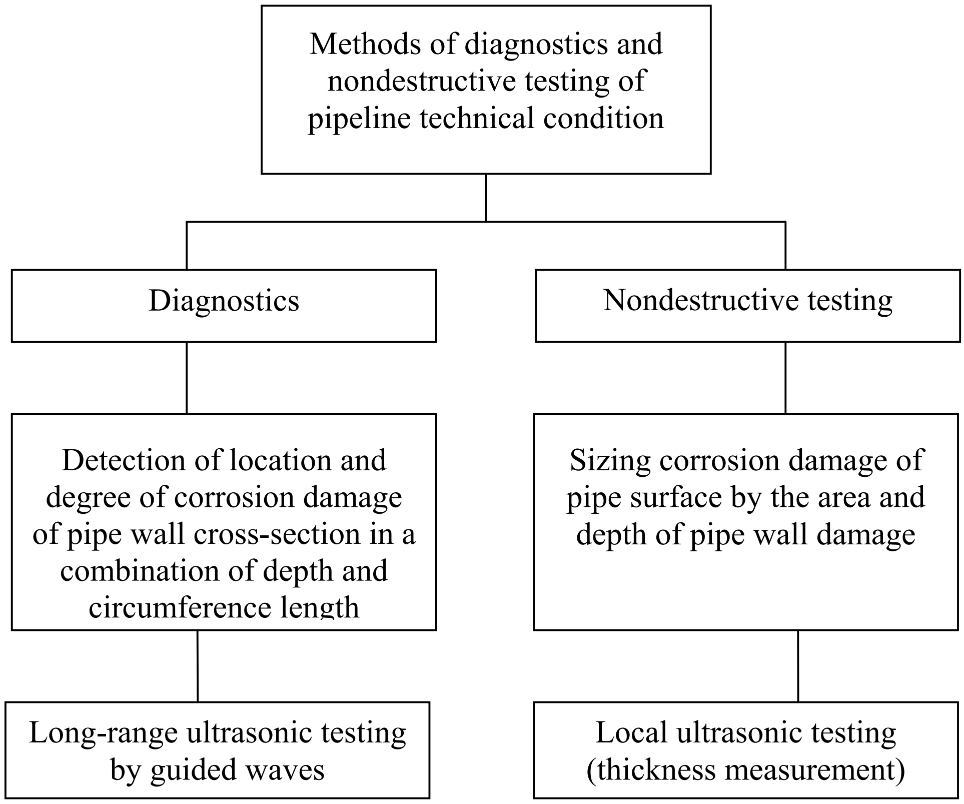


Fig. 5. Integrated methods of diagnostics and monitoring of technical condition of pipelines

Application of the technology and technique of long-range guided wave UT requires complete understanding of the factors affecting the test results, and practical experience of result interpretation.

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