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The features of the guided wave excitation and propagation at testing of pipes

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The features of the guided wave excitation and propagation at testing of pipes

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Abstract. The generalized integral solutions of the problem connected with excitation and propagation of torsional waves by electromagnetic-acoustic transducers in unloaded pipes and under conditions of loading on contact viscoelastic media, taking into account excitation parameters (frequency and geometry of the transducers), geometry, viscosity and elastic characteristics of pipe material and surrounding media, are presented. The amplitude of angular displacements of the torsional waves in pipes is estimated from the point of choice of frequency band, scanning distance and sensitivity estimation in guided wave testing of the pipes with various types and sizes. The numerical and experimental estimation of influence of the surrounding media viscoelastic characteristics on attenuation of the torsional T(0,1), longitudinal L(0,1) and flexural F(1,1) waves in the pipe is performed. The model of acoustic path of the guided wave technique on multiple reflections for testing the pipes with fixed sizes is presented and the guided wave technique sensitivity to defects depending on quantity of the received reflections, clamping force of the acoustic transducer and unwanted mode amplitude which is restricting the sensitivity to the defects is estimated.

1. Introduction

In recent decades, the guided wave technique of acoustic non-destructive pipe testing based on the use of the guided elastic waves, which are able to propagate along extended objects at considerable distance, and providing an opportunity to improve testing efficiency during instant testing of pipelines has developed rapidly [1]. In most cases the guided wave technique is applied for main oil and gas pipelines testing to detect flaws in the form of extended and single-point corrosion damages, mechanical damages in the form of dents, pipe ovality, surface cracks, scratches, tearings, etc. The guided waves of lower order mode are used during the guided wave technique due to high efficiency of their excitation, low attenuation and simplicity of the obtained data interpretation [2-4].

The use of the torsional wave during pipe testing is efficient in terms of velocity dispersion absence, higher sensitivity to the defects and lower attenuation [4-7]. The longitudinal modes of the first and the second orders are also applied [2, 8, 9] as they have low value of the dispersion in the range of the frequencies under investigation.

The ways of excitation of the guided waves, detecting flaws of different forms and sizes, wave transformation on defects and peculiarities in pipes, influence of viscoelastic media on wave attenuation are widely discussed in foreign literature [8, 10-15]. The most studies on the guided wave technique is devoted to the increase of technique sensitivity, based on the focusing of the guided

waves, development the new transducer design and new ways of wave excitation and reception, mathematical analysis of echograms and definition of spectral component of pulse from defect, the decrease of unwanted mode amplitude and acoustic noise [15-22]. Nevertheless, the claimed smallest detectable size of defect by the modern flaw detectors realizing the guided wave is 2% of pipe cross section [3, 9, 17], that restricts the technique sensitivity.

Analysis of propagation features, efficiency of excitation and reflection from defects of torsional waves depending on loading conditions, geometric pipe sizes, clamping force of transducer to the cylindrical pipe surface and excitation frequency is required for estimation of possibilities of the guided wave testing technique.

2. The features of guided wave excitation and receiving

It is known, that axisymmetric longitudinal L, torsional T waves and antisymmetric flexural F waves can propagate in long range cylindrical objects [9, 23]. The geometric dispersion of the velocity, that is dependence of phase and group wave velocities on oscillation frequency and cross dimensions of cylindrical object, is peculiar for the guided wave (figure 1). The application of the guided waves in frequency area of the significant velocity dispersion and existence of several modes lead to distortion and attenuation of signals from defects and to the difficulty of interpretation of the distorted signals produced in the pipe. That's why the torsional wave of zero order T(0,1), where the dispersion is absent, is usually used when constructing the guided wave technique equipment for pipeline testing, and the longitudinal waves of zero L(0,1) and the first L(0,2) orders in frequency area of the lowest velocity dispersion are also used.

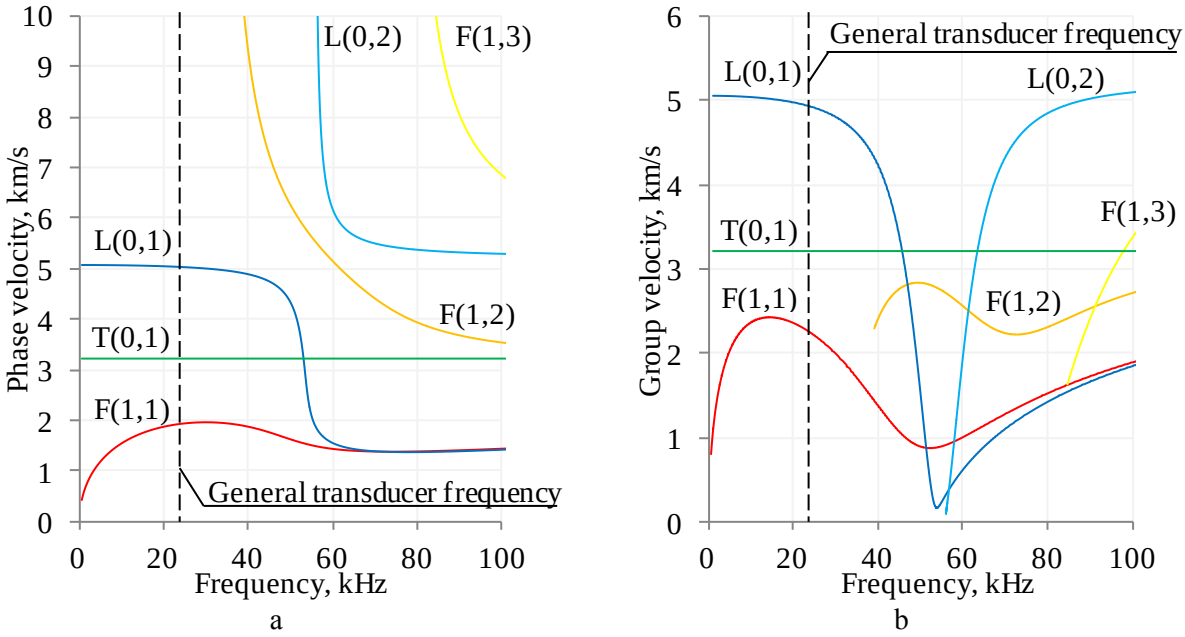

Figure 1. Phase (a) and group (b) velocities for pipe with diameter 32 mm and wall thickness 4.2 mm.

There is one angular displacement component in the torsional wave (figure 2), the movement is symmetric about the pipe axis and is represented as rotation of the pipe cross section about this axis. There are two displacement components in the longitudinal waves: axial and radial (figure 2); the movement is symmetric about the pipe axis and the longitudinal displacement component prevails. There are all three displacement components in the flexural waves (figure 2), the movement is antisymmetric about the pipe axis and is represented as combination of axial, radial and angular displacements, symmetrically distributed about radial-axial surfaces, the quantity of which increases with circumferential order. In this case, the joint use of the symmetric and the torsional waves allows

providing the best sensitivity to flaws with various orientations (transversal and longitudinal cracks) [4, 12].

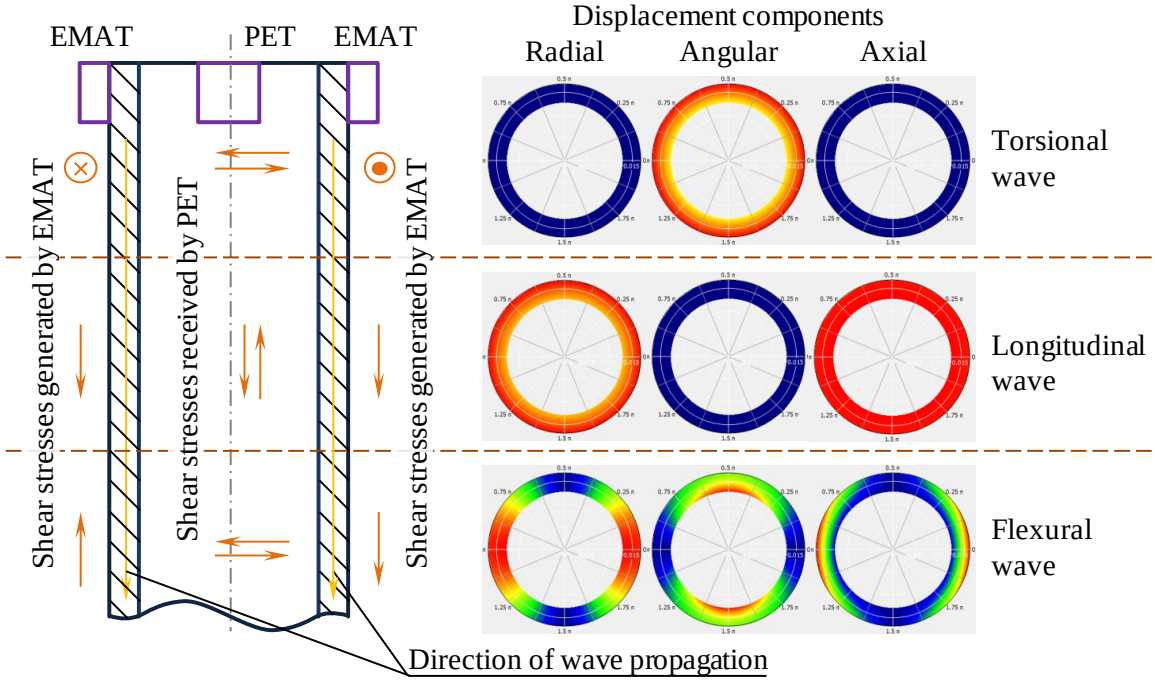

Figure 2. Approach to excitation and receiving of the guided waves at the method of multiple reflections and distribution of the displacement components in the pipe cross section.

When displacement curves in various types of the waves are known and radiators and receivers are orientated in a certain way about the pipe axis, it is possible to generate and receive the axisymmetric torsional and the longitudinal waves, and the flexural waves of low order modes as well (figure 2).

3. Numerical model

3.1. A model description

The investigation of the torsional wave propagation behavior in pipes under loading conditions on viscoelastic media is based on the physical model of excitation and propagation of the torsional wave in the endless (finite length) pipe [7, 19, 24] with external radius a and internal radius b, defined by the density ρ, elastic modulus λ and μ and dynamic viscosity η (figure 3). It is supposed, that the torsional wave transducer is located on the side of external pipe surface and produces stresses τ, tangential to the pipe envelope and uniformly distributed along its perimeter, in the limited area with L in length (the latter can be produced with the use of both contact piezoelectric and noncontact electromagnetic-acoustic transducers).

The case of contact between pipe with internal and external pipe surfaces and surrounding media is described by the slip coefficient on the boundary of pipe with external α_{12} and internal media α_{13}. It should be noted, that the mentioned slip coefficient allows describing "soft" bonding of two bodies and estimating deviation from conditions of "hard" contact ($\alpha_{12,13} = 1$), or "slip joint" coupling ($\alpha_{12,13} = 0$), leading to the failure in transferring of displacement components and stresses through interface between media [25]. The physically proved definition of α_{1n}, is ratio of acoustic impedance of the pipe and the surrounding media:

$$\alpha_{1n} = \frac{\rho_n \cdot C_n}{\rho_1 \cdot C_1} = \left(\frac{\rho_n \cdot \mu_n}{\rho_1 \cdot \mu_1} \right)^{-1}, \quad (1)$$

where ρ_n is a material density, μ_n is a shear modulus, C_n is an ultrasound wave velocity in the n-th medium, $n = 1, 2, 3$ are indexes corresponding to the pipe, external and internal media respectively .

The elastic torsional oscillations are produced in the body of the pipe, the surrounding internal and external contact media under tangential forces. Displacements in them $u_{n\varphi}(t,r)$ are described by the equations of movement of viscoelastic contracted body like Kelvin-Voigt's , solution of which is an expression for the angular displacement amplitude $U_{1\varphi}(r, z, \omega)$ in pipe, defined in the form of integral [24]:

$$U_{1\varphi}(r,z,\omega) = \int_{-\infty}^{\infty} \left[A_1(k)J_1(r\beta_1) + B_1(k)Y_1(r\beta_1)\right]\exp(ikz)\frac{dk}{2\pi}, \tag{2}$$

where $J_1(r\beta_1)$ is Bessel function of the first kind of the first order, $Y_1(r\beta_1)$ is Bessel function of the first kind of the second order, $A_1(k)$, $B_1(k)$ are integration constants, defined from boundary kinematic and force conditions on interface between media, k is a wave-number vector,

$$\beta_1 = \sqrt{\frac{\omega^2\rho_1(\mu_1 - i\omega\eta_1)}{\mu_1^2 + (\omega\eta_1)^2} - k^2}\ . \tag{3}$$

The obtained solution describes fields of the elastic displacements with any geometric sizes of the pipe (diameter and wall thickness), any excitation parameters (transducer sizes, surface stress amplitude, frequency band), any viscoelastic properties of pipe material and surrounding media. Theoretical study of the main torsional wave propagation characteristics in unloaded pipes and pipes loaded by the viscoelatic contact media is carried out from the point of influence of operating frequency, distance to the observation point and contact conditions. The pipes with diameters at the range of 32-1020 mm and wall thickness with values from 4,2 to 16 mm are chosen for this study.

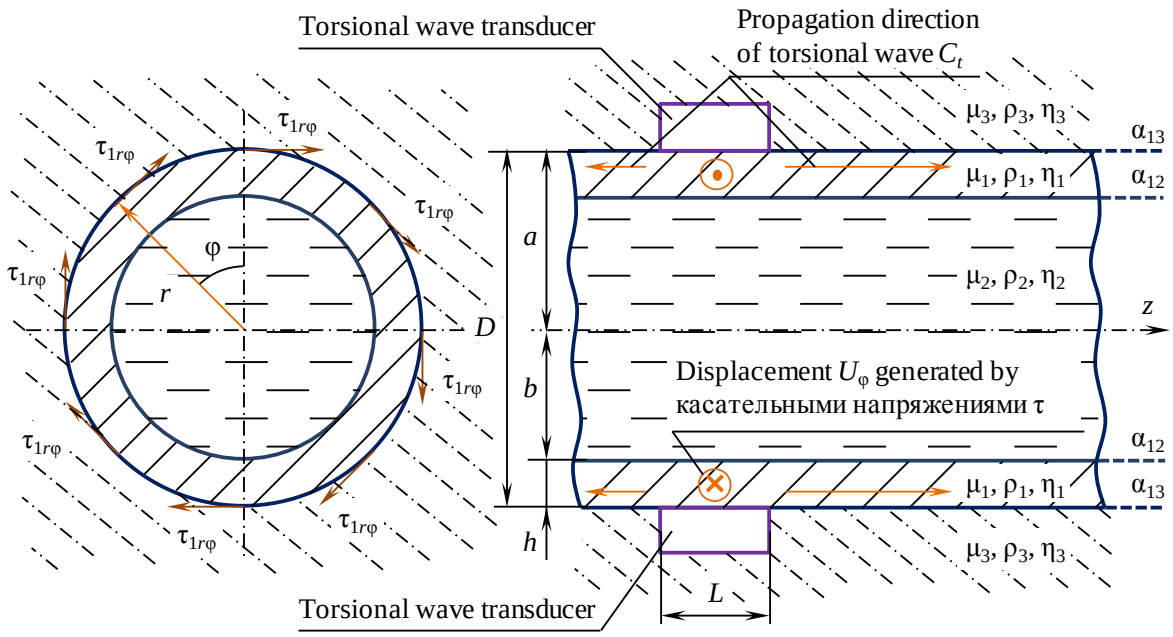

Figure 3. Physical model for calculation of displacements in torsional wave.

The calculation of integral expressions for angular displacements is carried out numerically using trapezium method in software MATLAB.

3.2. Unloaded pipes

The results of study for the unloaded pipes are presented in figure 4. Expressed natural resonances over pipe diameter and antiresonances through pipe wall thickness are observed at the range of the frequencies under investigation, used in the guided wave testing (from 1 to 200 kHz) (figure 4). The resonance over the diameter corresponds to the round number of wave length ($D = 0.96\lambda_{1R}$), and the antiresonsnce through the pipe wall thickness corresponds to the round number of the wave length quarter ($h = n \cdot \lambda_{2A}/4$, where n is a round number). As it follows from the given graphs, the displacement amplitudes can change by 6 orders (at the range from 10^{-7} to 10^{-13} m) under frequency change from 1 kHz to 200 kHz even out of the resonances.

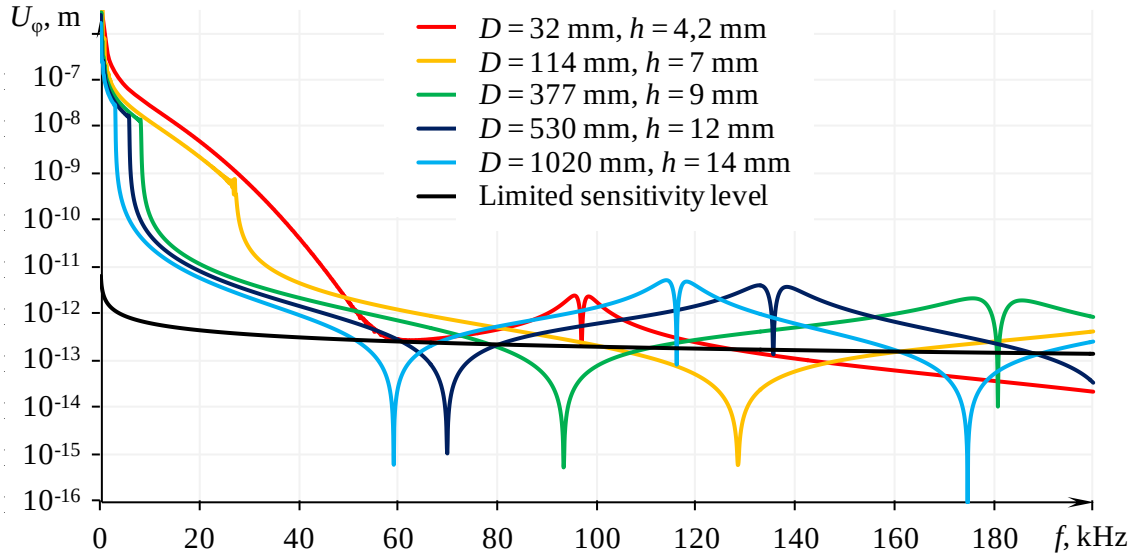

Figure 4. Dependencies of frequency on displacement amplitudes of the torsional wave for unloaded pipes with different diameters and values of wall thickness.

The angular displacements in the torsional wave decrease with distance according to the exponential law with an attenuation coefficient proportional to the dynamic viscocity η, and expressiveness of resonances decreases in this case.

When developing equipment of the guided wave testing, optimal choice of transducer aperture is important. The studies show, that the increase of torsional wave transducer aperture length L causes the increase of the angular displacement amplitude U_φ at the range with of values of L, essentially lower than the torsional wave length λ_T. If the values of λ_T are close to the value of the transducer aperture L, then the displacement amplitude U_φ approaches zero, that is explained by the interference of the waves radiated by elementary radiators along the transducer aperture at the observation point.

3.3. Loaded pipes

Pipeline coating, soil and properties of the transported product (oil, gas, water) have a great impact on scanning range [15]. Influence of the viscoelastic characteristics and contact conditions on values of angular displacement amplitudes U_φ of the torsional waves in a steel pipe is investigated using the developed model.

Air (an unloaded pipe), soil (clay, sand, ground), bitumen insulation (polyethylene), concrete are used as material of external media for calculation, and air (an unloaded pipe) is as material of internal medium; the viscoelastic properties of them are presented in table 1. The presence of external contact media causes the decrease of the torsional wave displacement amplitude in frequency area till the first resonance (figure 5).

Figure 6 illustrates dependencies of the displacement amplitudes U_φ normalized about the unloaded pipe on the slip coefficient α_{12} for external media with various viscoelastic properties at the fixed

frequency. Inverse proportional dependence of the displacement amplitude on α_{12} close to linear one is obtained at the range of values of the slip coefficients under investigation. According to figure 6, the displacement amplitude is decreasing by 35 dB for the pipe in bitumen isolation under the conditions of complete contact ($\alpha_{12} = 0.06$) at the distance of 10 m, and by 10 dB for the pipe loaded on clay when $\alpha_{12} = 0.03$ comparing to the unloaded pipe. Deterioration of contact degree causes great decrease of the displacement amplitude attenuation in the torsional wave. Thus, when the contact of bitumen isolation and the pipe is incomplete ($\alpha_{12} = 0.06$), the displacement amplitude is increasing by 15 dB comparing to the complete contact. It is worth noting, that dependence of the displacement amplitude on the slip coefficient is less essential for pipes with greater diameters.

Table 1. Viscoelastic properties of investigated media.

Medium	Parameters					
	Density (kg/m^3)	Longitudinal wave velocity (m/s)	Transverse wave velocity (m/s)	Shear modulus, GPa	Dynamic viscosity (Pa·s), f = 30 kHz	Slip coefficient
	ρ	C_l	C_t	μ	η	α_{max}
Low carbon steel	7800	5850	3250	82.3	150	-
Concrete	2200	4150	2400	12	640	0.203
Bitumen insulation	1180	2730	1430	2.4	350	0.066
Clay	1600	1900	500	0.4	5.5	0.032
Sand	1500	1530	370	0.14	2.9	0.022
Ground	1500	1300	200	0.06	1.5	0.018
Water	1000	1500	0	0	$7.2 \cdot 10^{-4}$	0
Air	1.3	340	0	0	$1.0 \cdot 10^{-5}$	0

It should be noted, that any internal medium of pipeline (working substance is either compressed gas, or water, or oil, etc) refers to the media with low shear elasticity (low values of μ_2 and $\alpha_{13} = 0$) and almost doesn't have any impact on the displacement amplitude in the torsional wave.

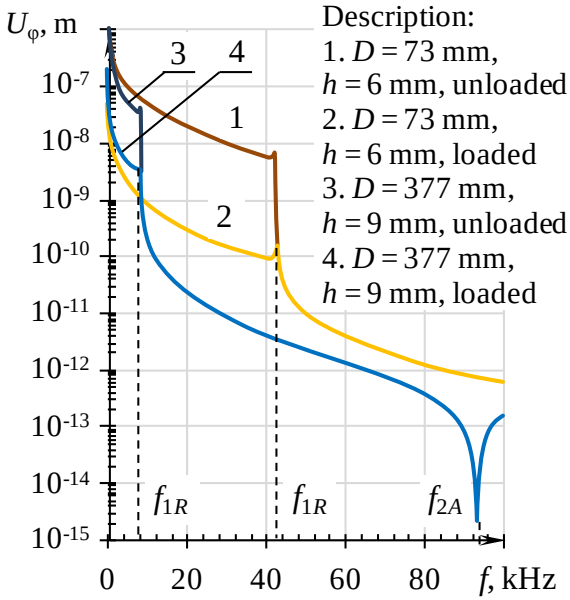

Figure 5. Influence of bitumen insulation on displacement amplitudes of torsional wave in pipes with diameters 73, 377 mm and wall thickness 6, 9 mm respectively.

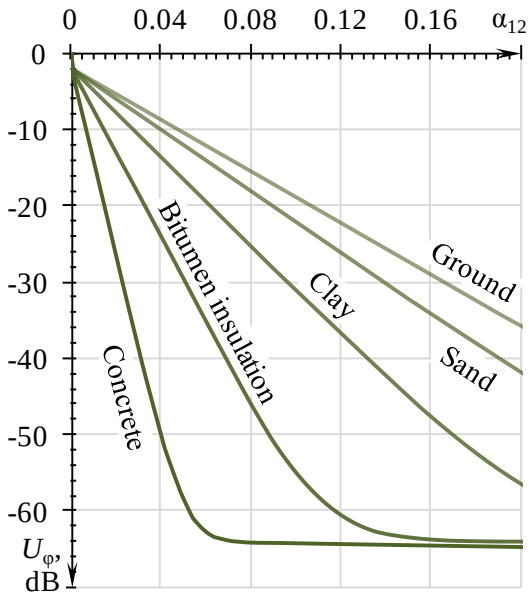

Figure 6. Influence of slip coefficient on attenuation of torsional wave in pipe with diameter 73 mm and wall thickness 5.5 mm.

Figure 7 illustrates the generalized results of investigation of the displacement amplitudes in the torsional wave in the pipe with diameter of 73 mm under the conditions of reradiation into various surrounding media represented in the form of dots on surface “dynamic viscosity – slip coefficient”.

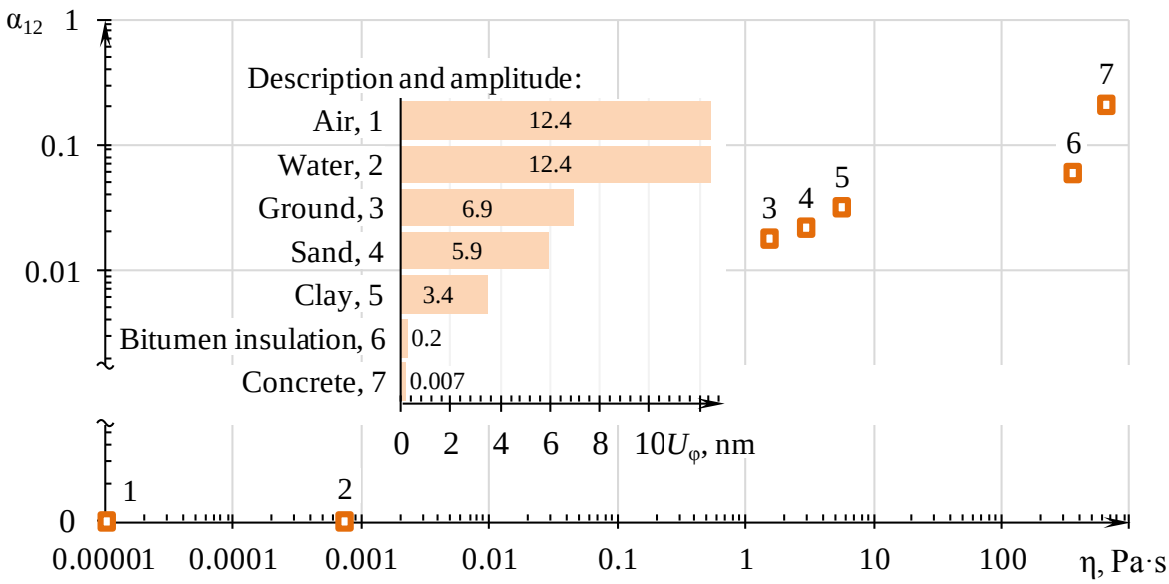

Figure 7. Distribution of contact media on their viscoelastic properties and displacement amplitudes at the surface “dynamic viscosity – slip coefficient”.

4. Experimental results

In order to prove validity of the theoretical results, obtained on the basis of the mathematical model, comparative experimental investigations of displacement amplitudes in the torsional wave were

carried out in the steel pipes with diameters of 18, 32, 57 and 73,5 mm and wall thicknesses of 4,2 mm, 4,5 mm, 5 and 5,5 mm respectively and 950 mm in length at the operating frequency equaled to 25 kHz. The pipe placed into a plastic container was loaded by contact external (water, wet sand, dry ground, granulated clay) and internal media (water, dextrin as simulator of viscous fluid).

The installation of the guided wave testing described in [7] was used for experimental investigations. EMA transducers operated by electrodynamic mechanism were used as radiators, piezoelectric transducers on the basis of shift piezoceramics like NFI50 (НФИ50 in Russian) were used as receivers. [7]. As an example, figure 8 illustrates the registration results of the torsional wave echo-pulses in the pipe with diameter of 73 mm, unloaded or filled with water. It is worth noting, that echo-pulse amplitude doesn't change essentially in the case of water and dextrin loading from both external and internal sides of pipe, it is connected with the absence of reradiation effect of the torsional waves into liquid media due to impossibility of excitation of shear displacements in the latter (figure 8). Degree of the acoustic noises caused by radiation of unwanted oscillation modes (longitudinal and flexural) decreases essentially comparing to the unloaded pipe (by 1,3 times and 1,8 times under water and dextrin loading respectively).

The generalized diagrams of echo-pulse amplitude attenuation in the guided waves measured in decibel per meter for the pipes with diameter of 32 and 73 mm are represented in figure 9 and allow estimating their attenuation at any distance.

Experimental results of the investigation of pipe loading with various diameters corresponds with calculation data satisfactorily (figure 10), that shows the validity of the suggested physical-mathematical model. Deviations can be caused by the differencies in the media characteristics used for the experiment from the properties used in the calculated models.

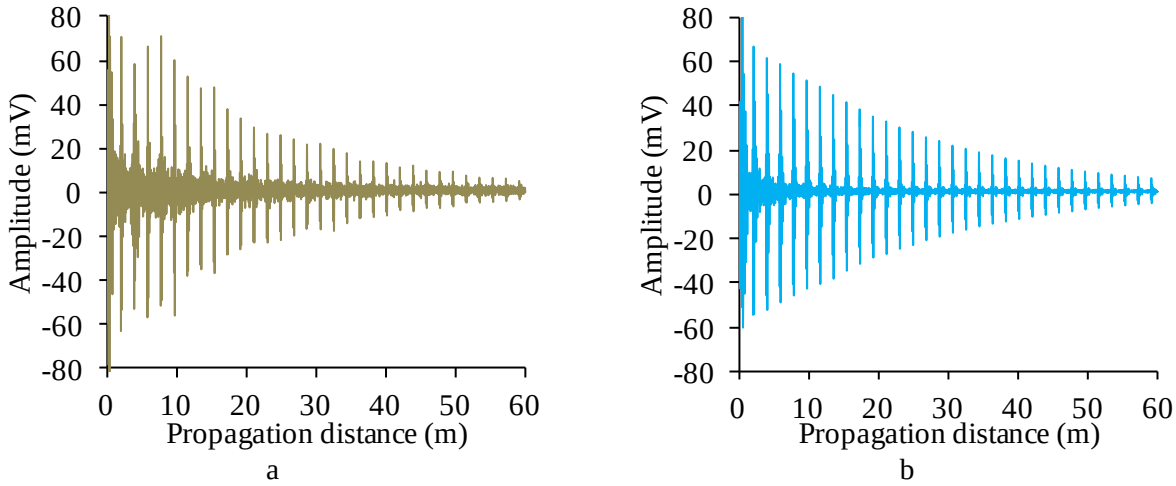

Figure 8. Echo pulse series of multiple reflections from pipe ends for unloaded pipe (a) and filled with water (b): pipe diameter 73 mm and wall thickness 5.5 mm.

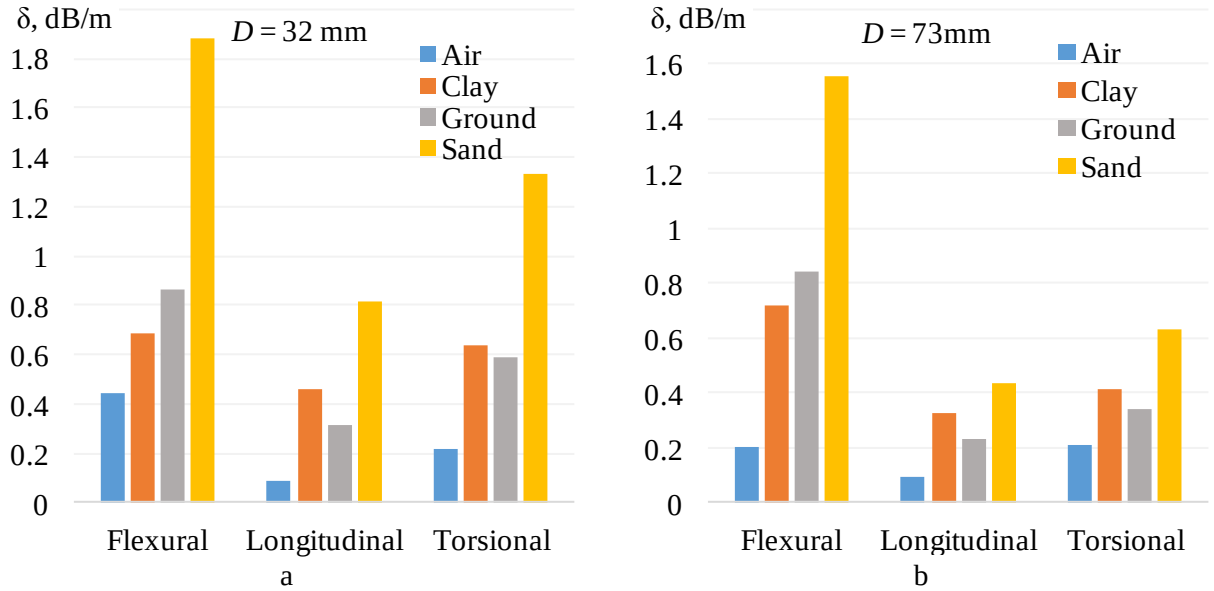

Figure 9. Generalized diagrams of echo pulse amplitude attenuation of guided waves for pipe with diameter 32 mm (wall thickness 4.2 mm) (a) and pipe with diameter 73 mm (wall thickness 5.5 mm) (b) loaded by ground, sand and clay.

5. The method of the multiple reflections

In the case of pipe testing with fixed sizes where the ends are free, the series of reflections multiply rereflected from the free pipe ends and defects can be formed (figure 11). The main technique feature is that the coherent amplification effect of echo-signals from the defects on further reflections (proportional to n) is observed under conditions of multiple rereflections from defects and pipe ends; it allows improving the sensitivity to the defects of small sizes.

The acoustic path of multiple reflection technique for pipe testing is defined by the formula [26]

$$U_{dn} = U_0 \cdot n \cdot D_d^{2(n-1)} \cdot R_d \cdot R_e^{n-1} \cdot e^{-2\delta L(n-1)} \cdot e^{-2\delta l}, \quad (4)$$

where U_{dn} is an echo-pulse amplitude from defect on the n-th reflection, U_0 is a probing pulse amplitude, D_d and R_d are transmission and reflection coefficients of acoustic waves from a defect, R_e is a reflection coefficient at the interface “testing object surface – transducer”, δ is an attenuation coefficient in an object, L is a length of testing object, l is a distance to defect.

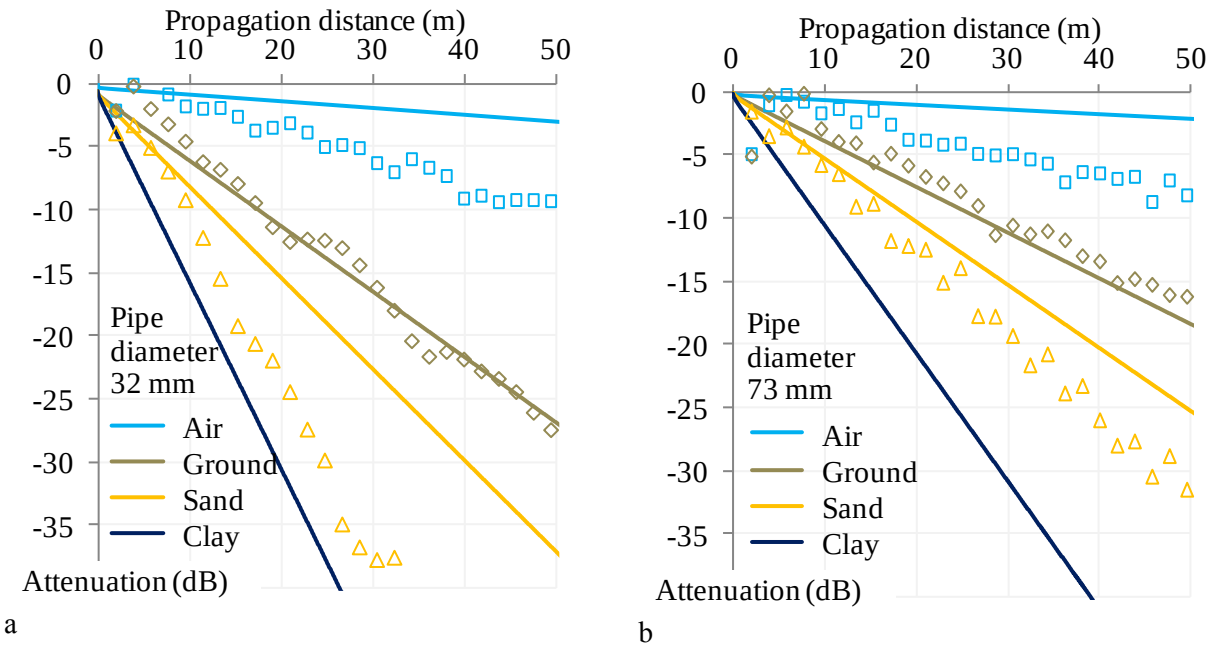

Figure 10. Theoretical (lines) and experimental (markers) dependencies of echo pulse amplitude attenuation from propagation distance of torsional wave for pipe with diameter 32 mm (wall thickness 4.2 mm) (a) and pipe with diameter 73 mm (wall thickness 5.5 mm) (b) loaded by ground, sand and clay.

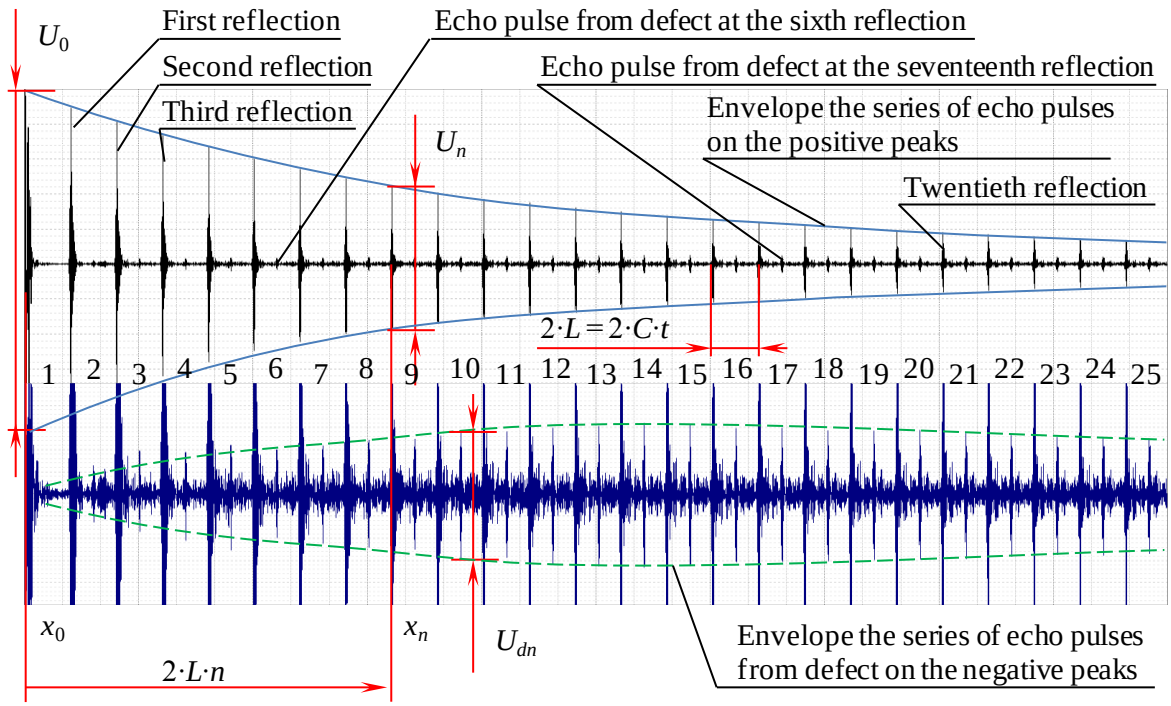

Figure 11. Echo pulse series of multiple reflections from pipe ends.

According to the plane acoustic wave propagation behavior in wave guides, the reflection R_d and transmission D_d through defect area of the wave guide are defined by change of its mechanical impedance [27].

Formula (4) describes the acoustic path for multiple reflection technique of extended objects with a use of torsional and longitudinal waves and without velocity dispersion and allows analyzing influence of the mentioned factors on testing efficiency and measurement accuracy of informative parameters [26].

As it follows from formula (4), the multiple reflection technique sensitivity is restricted by the attenuation in an object δ and reflection coefficient at the interface "testing object surface – transducer" R_e defined by the quality of acoustic contact (degree of transducer clamping to the testing object surface). The latter has an impact on the signal amplitude U_0 and level of acoustic noise.

The wave amplitude has the highest value when the transducer clamping force is the highest, but in this case the attenuation of the torsional wave echo-pulse series increases essentially. Dependencies of the torsional wave attenuation on the clamping force are presented in figure 12. It follows from the given dependencies, that the torsional wave attenuation in pipes with diameter of 18, 32, 57, 73 mm in terms of the same value of the first echo-pulse amplitude varies in an amount of 0,2 to 1,4 dB/m. The generalized dependencies of the average value of the reflection coefficient on the first echo-pulse amplitude from pipe end for pipes of various diameters are presented in fig. 13. The reflection coefficient varies in an amount of 0,78 to 0.93.

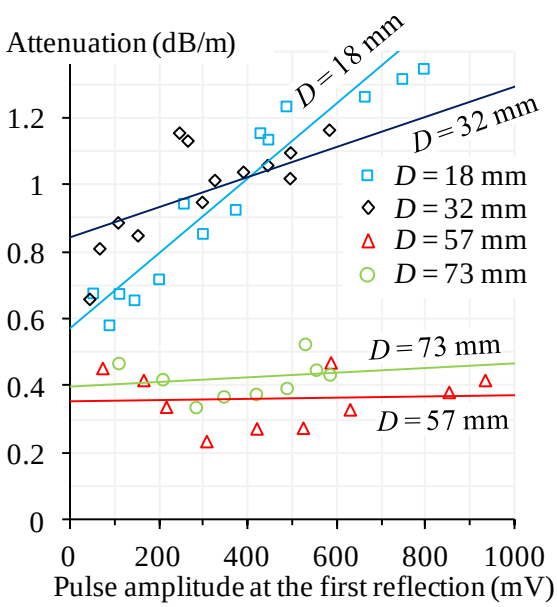

Figure 12. Experimental dependencies of echo pulse amplitude attenuation of torsional wave from pulse amplitude at the first reflection.

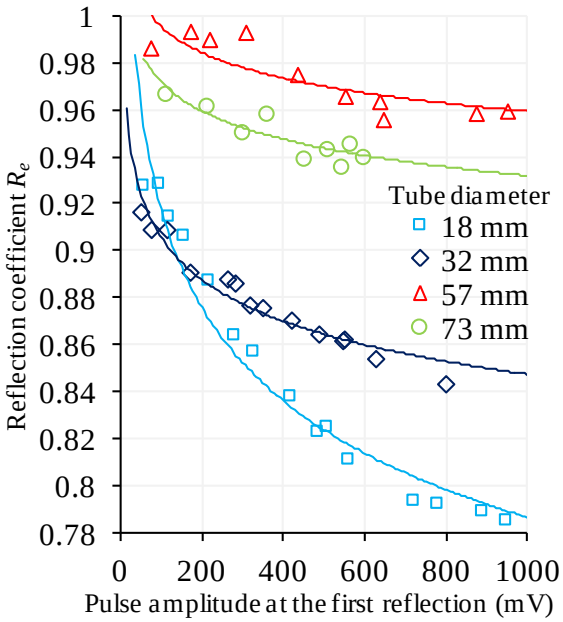

Figure 13. Calculated dependencies of reflection coefficient from pulse amplitude at the first reflection.

The developed models and investigated features of propagation, excitation and reflection of the guided waves from defects are used for realization of the guided wave testing for extended objects of such oil-field equipment as pump rods and blank rods (acoustic flaw detector for pump rods AFDPR, in Russian АДНШ) and pumping and compression pipes (acoustic flaw detector for pumping pipes AFDPP, in Russian АДНКТ) [1]. The results of the developed flaw detector exploitation show the sensitivity to rejectable flaws both in the process of manufacturing (thickness variation, cracks, barkfins, hair-line seams) and in the process of equipment operation (local and extended internal and external corrosion, pitting, cracks).

6. Conclusions

The developed theory, the investigated theoretical and experimental characteristics of excitation and propagation of the guided waves in pipes under loading conditions on viscoelastic media can be basis of validation of testing parameters from the point of choice of frequency band, estimation of scanning distance and technique sensitivity in the process of developing the guided wave testing technique of pipelines of various types and sizes and in various operating conditions.

The study of influencing factors on the sensitivity of the multiple reflection method in the guided wave pipe testing of limited sizes allows improving parameters of the acoustic contact to reach the highest sensitivity under minimization of acoustic noise influence caused by the generation of unwanted wave types.

Acknowledgments

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