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Acoustic Guided Wave Testing of Pipes of Small Diameters

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Abstract: Acoustic path is analyzed and main parameters of guided wave testing are substantiated applied to pipes of small diameters. The method is implemented using longitudinal L(0,1) and torsional T(0,1) waves based on electromagnetic-acoustic (EMA) transducers. The method of multiple reflections (MMR) combines echo-through, amplitude-shadow and time-shadow methods. Due to the effect of coherent amplification of echo-pulses from defects the sensitivity to the defects of small sizes at the signal analysis on the far reflections is increased. An opportunity of detection of both local defects (dents, corrosion damages, rolling features, pitting, cracks) and defects extended along the pipe is shown.

Introduction

Power efficiency of any heat supply system depends on such factors as technical state of manufacturing equipment, keeping the optimal operation modes, and quick detection and elimination of the defects occurred. Nowadays more than 80% of heat energy equipment exhausted its life-time; in this connection, the problem of developing the system of control, diagnostics and monitoring of heat energy equipment becomes urgent [1].

Among the tested heat energy objects, pipes for steam boilers and pipelines are the most common. In general, pipes are made of steel blanks in accordance with the technical specification (in Russian TY 14-3P-55-2001 and TY 14-3P-190-2004). Application of pipes for units of high and super-critical steam parameters stipulates for high demands to the quality of the pipe material. As far as steam boilers and pipelines are concerned, seamless cold-deformed, warm-deformed and hot-deformed steel pipes, including hot-pressed and hot-pressed reduced pipes are applied.

By tradition, pipes for heat energy engineering are controlled at production by means of ultrasonic, acoustic-emission, magnetic and eddy-current methods of non-destructive testing (NDT); the pipe wall thickness is measured by means of ultrasonic-calibrators [2-4]. Due to a considerable length of the controlled pipes, the pointed methods have a common drawback – the necessity of scanning the pipe solid, thus requiring the corresponding mechanized equipment and large production sites. This reduces the manufacturing efficiency of the units, complicates the system of object transportation and leads to the quick wearing out of transducers. Despite of the advantage provided by contactless operation, units of magnetic and eddy current control allow for revealing only surface and near-surface defects having definite dimensions. Identification of defects becomes complicated due to the absence of the unambiguous relation between mechanical properties of the object and magnetic parameters to be measured. The essential drawbacks are also the sensitivity to variations of the clearance, magnetic properties of the object and the necessity of additional demagnetization of the object. Contact ultrasonic methods require the presence of the immersion liquid and they are hard to implement for rolled stocks having small dimensions and low quality of surface treatment (hot rolled stocks).

In recent decade the guided wave acoustic methods became popular at the NDT market [5-8], allowing for performance of the express diagnostics of pipelines at essential increase of manufacturing efficiency of control due to the absence of scanning and at local access to the object. Means of guided wave control proposed at the market are intended, as a rule, for controlling the long-distance pipelines at operation; the sensitivity of methods being rather low in this case.

The paper presents the guided wave method of controlling the pipes having the limited length, developed by the authors. It is based on the method of multiple reflections, it uses longitudinal and torsional waves; and it is implemented by means of electromagnetic acoustic (EMA) transducers.

Applied approaches

It is known that normal Pochhammer waves (longitudinal L and flexural F) and normal torsional waves T can propagate in linearly extended objects (pipes). As for the normal waves, the geometric dispersion of the velocity is specific, that is, the relation between the phase and group velocities of waves and the frequency of oscillations and transverse dimensions of the shell. Dispersion curves are the main characteristic of normal waves (Fig. 1). Application of normal waves within the essential dispersion of the speed and existence of several modes leads to distortion and attenuation of signals due to defects and to the complexity of interpretation of distorted signals appearing in the multi-mode wave guide. Distortions are caused by both variation of phase relations between signals transmitted by various types of waves with the distance increase, and by variation of distribution of oscillations along the cross-section. In this relation, when designing the apparatus for the guided wave control, the torsional wave T(0,1) of zero order without any dispersion is applied, as a rule, and also the axial symmetrical wave L(0,1) at the area of minimum dispersion of velocity. Under these circumstances, the axial symmetrical wave L(0,1) is propagating at the velocity of the rod wave

$$C_{S0} = \sqrt{E/\rho}\,, \qquad (1)$$

and the torsional one T(0,1) is propagating at the velocity of the transverse wave

$$C_{T0} = \sqrt{G/\rho} \qquad (2)$$

where E, G are the Young module and the shear module, correspondingly, ρ is the density of the object material.

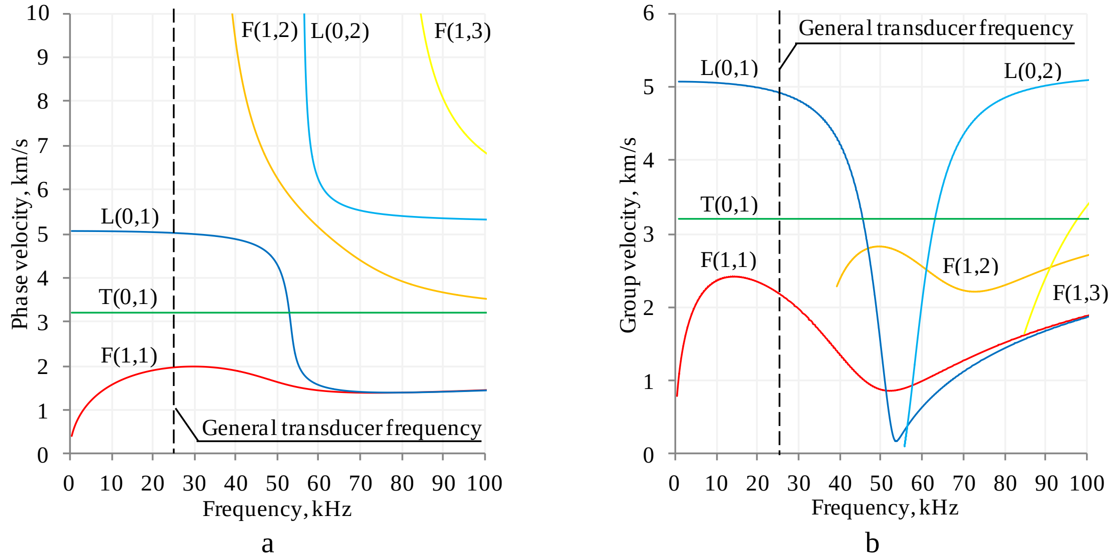
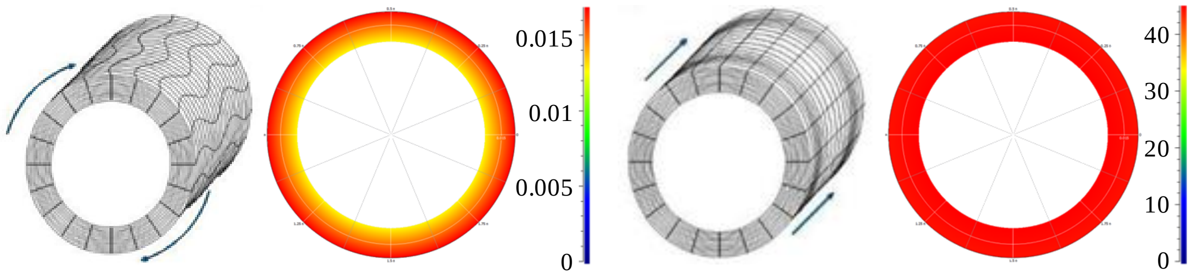


Fig. 1 Dispersion curves of phase (a) and group (b) velocities in the axial symmetrical $C_L(0,1)$ and torsional $C_T(0,1)$ waves, having the diameter 32 mm and wall thickness 4.2 mm.

There is only one angular component of displacements in torsional normal waves (Fig. 2a), it is the symmetrical motion with respect to the axis *z* and it represents the rotation of the transverse section of the pipe with respect to this axis. There are two components of displacements in longitudinal normal waves (Fig. 2b), they are the axial and radial ones; the motion takes place here symmetrically with respect to the axis of the *pipe* and the longitudinal component of displacements is prevailing.



a b

Fig. 2 Normal waves in cylindrical shells and the corresponding diagrams of displacements in the torsional T(0,1) (a) and axially symmetrical L(0,1) (b) waves

Application of the fundamental mode of the torsional wave at pipe control is reasonable due to a higher sensitivity to defects and low attenuation [9]. The joint application of the symmetrical and torsional waves allows for providing the best identification ability for defect of different orientation (transverse and longitudinal cracks) [10-11].

In order to assess the possibilities of the guided method of control as applied to pipelines of different dimension types, the preliminary analysis of the acoustic path of the method has been performed to substantiate the parameters of control. In particular, basing on the generalized integral solutions of the problem for excitation and propagation of torsional waves by EMA transducers in free pipes, the efficiency of excitation of acoustic waves in them has been investigated with regard to geometrical dimensions of a pipe and parameters of excitation [9, 12].

The acoustic path of the method for multiple reflections at the pipe control is described by the formula [13]

$$U_{dn} = U_0 \cdot n \cdot D_d^{2(n-1)} \cdot R_d \cdot R_e^{n-1} \cdot e^{-2\delta L(n-1)} \cdot e^{-2\delta l}, \quad (3)$$

where U_{dn} is the amplitude of the echo-pulse due to the defect at the *n*-th reflection, R_e is the factor of reflection from the boundary “object surface – transducer”, δ is the attenuation factor of the object, *L* is the length of the object, *l* is the distance to the defect, R_d and D_d are the factors of reflection and transparency of acoustic waves from the defect respectively.

In terms of multiple re-reflections from defects and face ends of the pipe, the effect of a coherent amplification of echo-signals from defects for the consequent reflections (proportionally to n) is observed, thus allowing to improve the sensitivity to low-sized defects.

In accordance with the laws of distribution of plane acoustic waves in wave guides, reflection and passing through the defective area of the wave guide is determined by its mechanical impedance Z = ρ*CS (s is the area of the wave guide cross-section)*. When the properties of the wave guide material do not vary (ρ*C = const*) and only its cross-section is changed, the factors of reflection R_d and transparency D_d through the defective area are determined by the following formulas [14]:

$$R_d = \frac{S_2^{\,2} - S_1^{\,2}}{\left(S_1^{\,2} + S_2^{\,2}\right)^2 + 2iS_1S_2\cot(\omega l_d / C_0)}, \quad (4)$$

$$D_d = \frac{2S_1 e^{i\omega l_d / C_0}}{S_1 + S_2}, \quad (5)$$

where S_1 up to S_2 is the transverse section of the defect-free area of the wave guide and the area with the defect, l_d is the length of the defect along the axis, ω is the cyclic frequency of the wave, C_0 is the velocity of the rod wave.

Formulas (3) – (5) describe the acoustic path at implementation of the method for multiple reflections of long-distance objects with application of rod and torsional waves at the absence of velocity dispersion; and they allow for analyzing the influence of all the pointed factors on the efficiency of control and the accuracy of defining its information parameters.

It should be noted that when applying the torsional wave, the reflection from the defect accompanied by variation of the transverse section of the rod from S_1 to S_2 takes place due to both the decrease in the transverse section of the rod and reduction of the velocity of the wave propagation.

As for the defects which are the concentrators of mechanical stresses (cracks with low disclosure) and which do not change significantly the mechanical impedance of the pipe, we deal with the mechanism of radiation for acoustic emission waves from areas where the stresses exceed the average value along the section of the object of control when passing through the sounding pulse (tension-compression or torsion) [12]. Note, that these defects can be developed at operation of the heat energy equipment.

Equipment and results of control

The developed acoustic guided wave flaw detector is intended to control the pipes having the limited length 3-12 meters and small diameters ∅ 5 – 90 mm. The generalized structural scheme of the flaw detector is shown in Fig. 3. The principle of operation of the flaw detector implies the methods for multiple reflections combining the echo-through, amplitude-shadow and time-shadow methods. The method for multiple reflections is based on registration of echo pulses that are multiply (5-10 times) reflected from external and internal defects of the pipe wall and from the opposite face ends of the pipe. In terms of multiple re-reflections from defects and from the face ends of the pipe, the effect of coherent amplification of echo signals from defects at the consequent reflections is observed, thus allowing to improve the sensitivity to small-sized defects when analyzing the signal at long-range reflections.

The generator of the unit of the generator and preamplifier block (GPA) produces the electrical pulse supplied to the radiator of the unit of electro-acoustic transducers (EAT) thus leading to the appearance of the acoustic pulse propagated in the pipe at the velocity of the torsional or rod wave depending on orientation of the EAT with regard to the generating line of the pipe. The acoustic pulse, multiply reflected from defects of the pipe like continuity violation and from its face end, it received at the same face end by the EAT unit and it is transmitted to the preamplifier of the GPA unit as an electric signal. The amplifier performs further amplification of signals with the controlled coefficient; its amplification coefficient is chosen automatically, so that the measured signal could not face the limitation. The electric signal from the amplifier is transmitted to the input of the analog digital converter and then to the memory of the personal computer. Operation of the flaw detector is performed by means of a specialized software program.

Fig. 4 shows the registered oscillogram at multiple sonic test of the flawless pipe and the pipe with the local defect. The presence of defects in the pipe leads to appearance of echo pulses from defects at the area between the probing pulse and echo pulse from the face end, and also at consequent reflections as echo pulses that are symmetrically arranged between two neighboring reflections. In order to eliminate the influence of the quality of an acoustic contact and efficiency of excitation receipt of waves for various grades of steels on the results of control, the amplitude of the echo pulse from the defect is regulated in accordance with the amplitude of the first echo pulse from the face end of the object. The regulated amplitude of the echo pulse from the defect is the basis for the natural assumption of the validity or defectiveness of the pipe according to criteria of sorting out which can be determined with regard to the limiting deviation of the wall thickness from the nominal one. Criteria of sorting out of pipes with regard to the velocity and attenuation are chosen basing on the accumulated statistical information on types and degree of the hazard for the defects revealed at inspection.

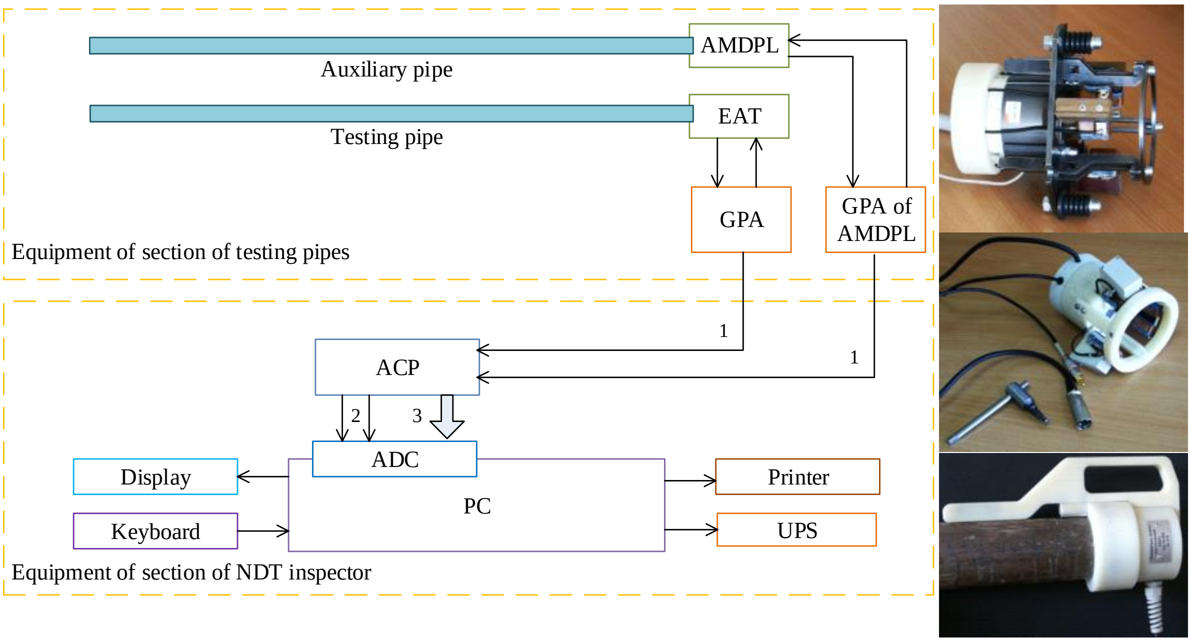
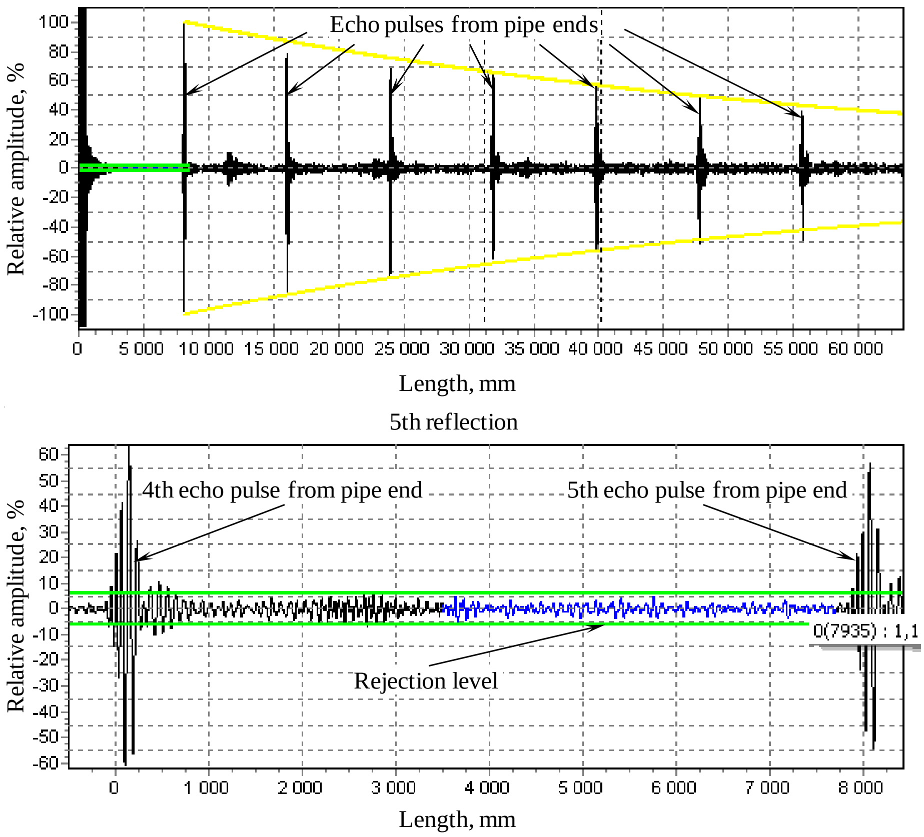


Fig. 3 The generalized flow diagram of the flaw detector and the type of EAT: AMDPL – acoustic measuring device of pipe length, EAT – electro acoustic transducer, GPA – generator and preamplifier block, ACP – programming amplifier, commutation and power supply, ADC – analog digital converter, PC – personal computer, 1-3 – data cables



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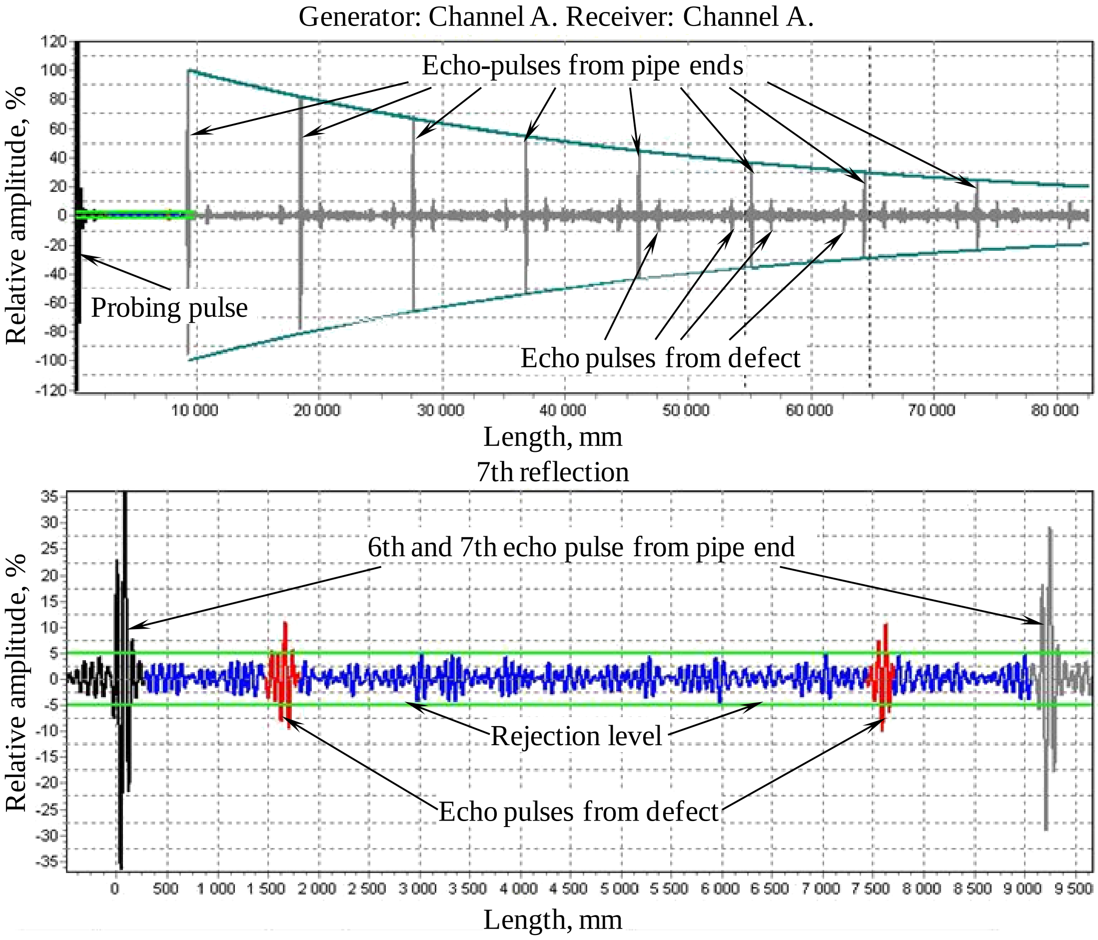

b

Fig. 4 Flaw patterns of the valid pipe (a) and the pipe with the local defect (b)

The basic measured characteristics of defects are:

- the amplitude of the echo pulse from the defect expressed in percent of the echo pulse from the opposite face end of the pipe (the factor of reflection for the first reflection R_1, %);
- the amplitude of the echo pulse from the defect at the N-th reflection expressed in percent of the first echo pulse from the opposite face end (the factor of reflection for the N-th reflection R_N, %);
- coordinates of the revealed defects along the pipe length (the distance from the transducer to the defect).
- the attenuation factor for echo pulses reflected from face ends of the pipe. This factor can be significantly increased at the presence of long-distance defects like corrosion on the internal or external surface of the pipe;
- the velocity of propagation of the torsional wave which can be significantly decreased at the presence of long-distance defects like corrosion, wall thickness variation and cracks.

For precise definition of the velocity and attenuation of waves, the flaw detector is equipped with the acoustic measuring device of the pipe length (AMDPL), its principle of operation being based on measuring the time of acoustic wave passing through the air space inside the pipe. The method provides the accuracy of the pipe length measuring within ±10 mm; and it can be applied, among other, as the measuring device for pipe lengths.

The echo pulse method allows for detecting the local defects: dimples, rolling laps, shells, corrosion damages (Fig. 5). The method for multiple reflections allows for revealing both localized and long-distance defects along the pipe length; it improves the sensitivity to small-sized defects and reduces the uncontrollable dead zone from the side of the acoustic signal input which is inherent to the echo pulse method. This reduction is due to the way of controlling from one of the face ends of the pipe.

Fig. 5 The revealed defects: a crack, internal and external local corrosion, internal and external multiple corrosion

Conclusions

The developed technique of the guided wave acoustic control of pipes possesses the following advantages: it does not require scanning and application of contact and immersion liquids and any kind of preparation of the surface of the controlled object; it possesses high efficiency; it has a rather high sensitivity to defects independently on the depth of their location and the distance to the transducer; it reveals the most risky defects which influence on the pipe life time.

There is a possibility to apply the developed techniques when controlling the pipes at their operation; the sensitivity being reduced a little in this case due to impossibility of obtaining the series of multiple reflections.

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