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NONDESTRUCTIVE TESTING OF THE PIPE INNER CAVITY

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Abstract: A new method of the state of pipe inner cavity testing is described. It is based on the exciting of Lamb waves in the wall and analysis of the amplitude - frequency characteristic or transient response.

Keywords: pipeline, Lamb waves, interference.

1   INTRODUCTION

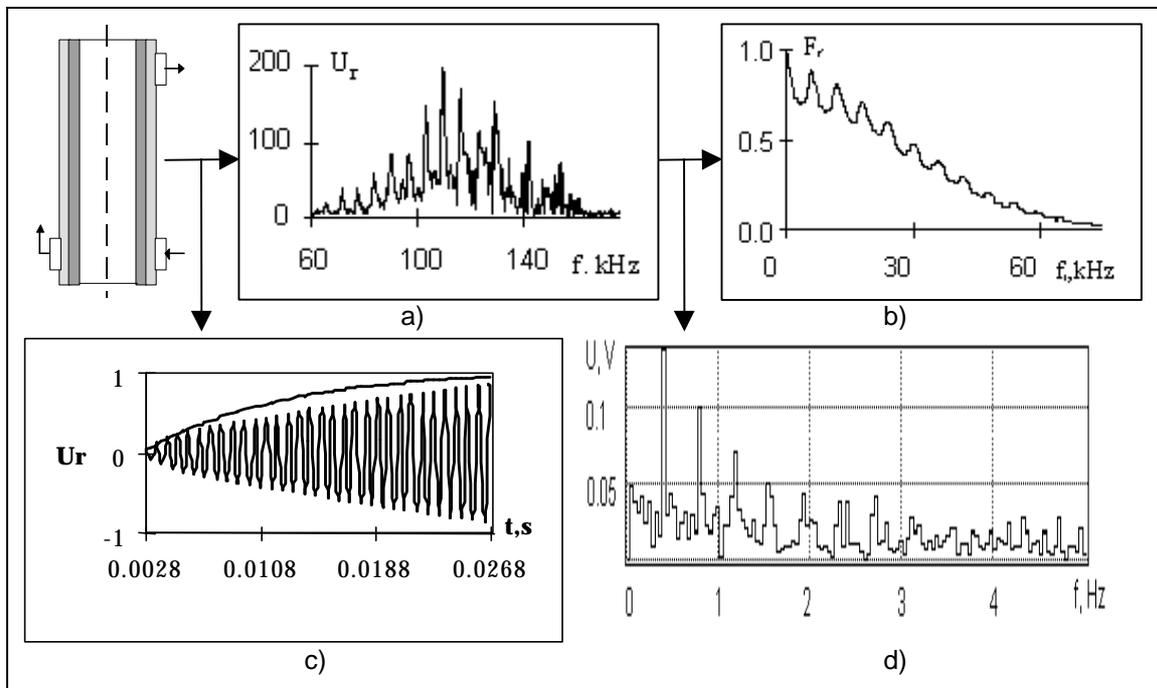The diagnosis of the inner cavity of pipeline must answer the questions:
- is the pipe empty or filled with liquid,
- is there any sediment on the outer surface of the pipe.

The testing of the filling of the pipe can be realized by transmitting – receiving of the longitudinal ultrasound waves across the pipe. The form of the pipe must be known and both sides of the pipe must be accessible for transducers mounting. The measurement of the thickness of sediment layer can be carried out by conventional means of thickness measurement, but the error is great: the sediment layer is porous, the surface of the layer is not correct, and, as a result the reflection of the waves, is weak.

2   PRINCIPLES OF TESTING

Our developed method is based on exciting of Lamb wave (flexural type) in several points of the pipe. The waves are transmitting by conventional transducer of the longitudinal waves in frequency band of 60…180 kHz for pipes with outer diameter 50…150 cm.

There are two ways of testing: by analysis of the amplitude – frequency characteristics (AFCh) and analysis of the transient response (Figure 1).

Figure 1. Methods of testing: a – AFCh, b – autocorrelation function, c - transient response, d – spectrum.

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3 METHODS OF ANALYSIS

3.1 Analysis in frequency domain

The exciting frequency is changing slowly in this case. The waves propagate in all directions from the transmitter that can be imagined as a point source. Waves, propagating in two opposite directions along the circumference, interfere. The amplitude – frequency characteristic theoretically must consist of equidistant placed resonance peaks. The sediments or liquid damp the waves, and the quality factor of the resonating pipe can be a measure for the sediment thickness. But practically we see the superposition of some systems of resonance peaks with a little different frequency (the resonance of neighboring sections of the pipe with different thickness of the wall and sediments). It is impossible to use well - known algorithms for measurement of quality factor. We offer following suggestion [1, 2]:

$$ n = \frac{\int\limits_1^2 \left| \frac{dU'}{dt} \right| \left| \frac{dt}{df} \right| df}{\int\limits_1^2 U' df} = \frac{\int\limits_1^2 \left| \frac{dU'}{df} \right| df}{\int\limits_1^2 U' df} \,, \tag{1} $$

where n - the readings of thickness measuring units on the indicator scale; $U' = U (1 - K)$; U - the voltage of the receiver; K - the value of noise restriction; $K \approx 0.1$.

We have made the hypothesis that the changes of the AFCh – superposition of partly resonance curves – could not have the steeping different as in separately taken resonance characteristics. This allows using correlation function and increasing the accuracy and repeatability of the measurements [3]:

$$ F(f_i) = \sum_{i=0}^{k} \sum_{m=1}^{k} U(f_m) \cdot U(f_{m+i}) \,, \tag{2} $$

where $F(f_i)$ - the value of autocorrelation function in the i point; f_i - the deviation of the frequency; $U(f_m)$, $U(f_{m+i})$ - value of AFCh at f_m and f_{m+i} frequencies; k = number of points converted into digital form and stored in PC memory AFCh; $m = 1 \ldots k$; $i = 0 \ldots k$. If $m + i > k$, $U(f) = 0$. The examples of autocorrelation function are shown in the Figure 2. The corresponding AFCh curves were taken out by turning of the pair "transducer - receiver" each time about 10 degrees perpendicularly to the pipe axle. They differ a lot, but the tangent of the autocorrelation functions at the beginning repeats well. Such experiments were made in segments with 0 and calibrated 10 mm thickness of sediment and natural sediment layer about 20 mm (correspondly Figure 2a, b, c). The steel pipe had an outer diameter 152 mm, wall thickness 8 mm.
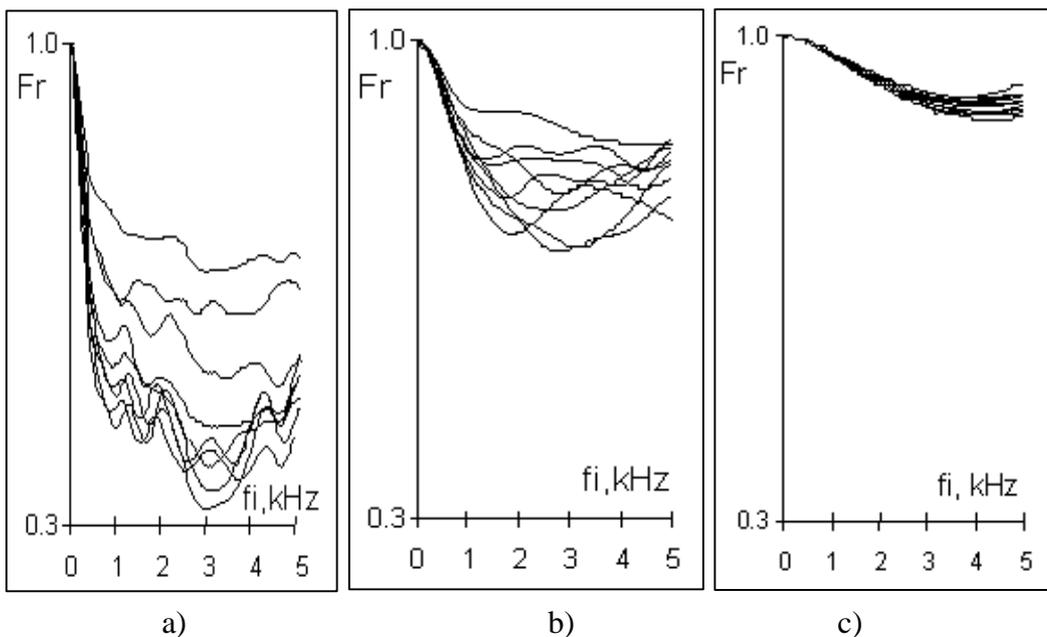
Figure 2. Repetition of results (beginnings of functions F_r): a - 0 mm sediment, b - 10 mm, c - natural pipe with unknown sediment.

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The following algorithm for calculation of the slope of the correlation function was developed:
  - finding the inflection point of the curve F_r till the first minimum,
  - finding the inverse slope of the curve in this point:

$$S_w = \frac{f_{w+1} - f_w}{F_{r(w+1)} - F_{rw}},$$ (3)

where f_w, F_{rw} are coordinates of inflection point, (point with number w); f_{w+1}, $F_{r(w+1)}$ - coordinates of next point,
  - calculating the slopes S_{w+1}, S_{w+2}, …, S_{w+i} and the average value $\langle S \rangle$:

$$\langle S_{w+i+1} \rangle = \frac{\langle S_{w+i} \rangle}{i+1} + \frac{S_{w+i+1}}{i+1}$$ (4)

till $\dfrac{S_{w+i+1}}{\langle S_{w+i+1} \rangle} > 1.4$,

  - calculating the average value according (4) with the slopes S_{w-1}, S_{w-2}, …, S_{w-j} till $\dfrac{S_{w-j}}{\langle S_{w-j} \rangle} > 1.4$

or $w\text{-}j < 3$, $i = 1, 2, 3, …$; $j = 1, 2, 3, ….$
  Such algorithm shows considerable insensibility to the noises.
  The assembly of the average values $\langle S \rangle$ for the curves (Figure 2 a – c) is shown in the Figure 3.

<S> can be used as a measure of sediment thickness. The repetition of the results in general is much better as in the measurements according formula (1). The repetition of the results in natural pipe is better then in the pipes with calibrated thickness of sediment. Perhaps the calibrating - preparing with turning lathe - destroys the inner structure of sediment layer (cracks of the layer).
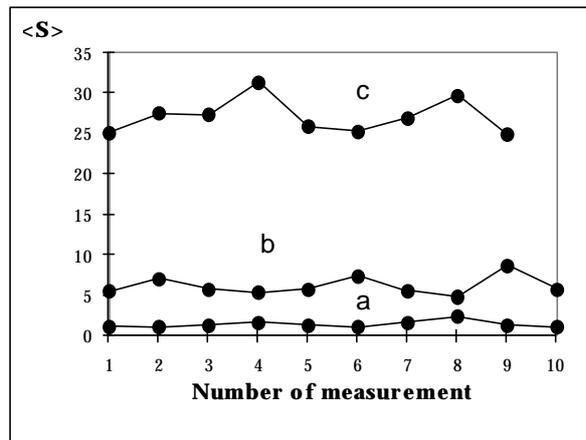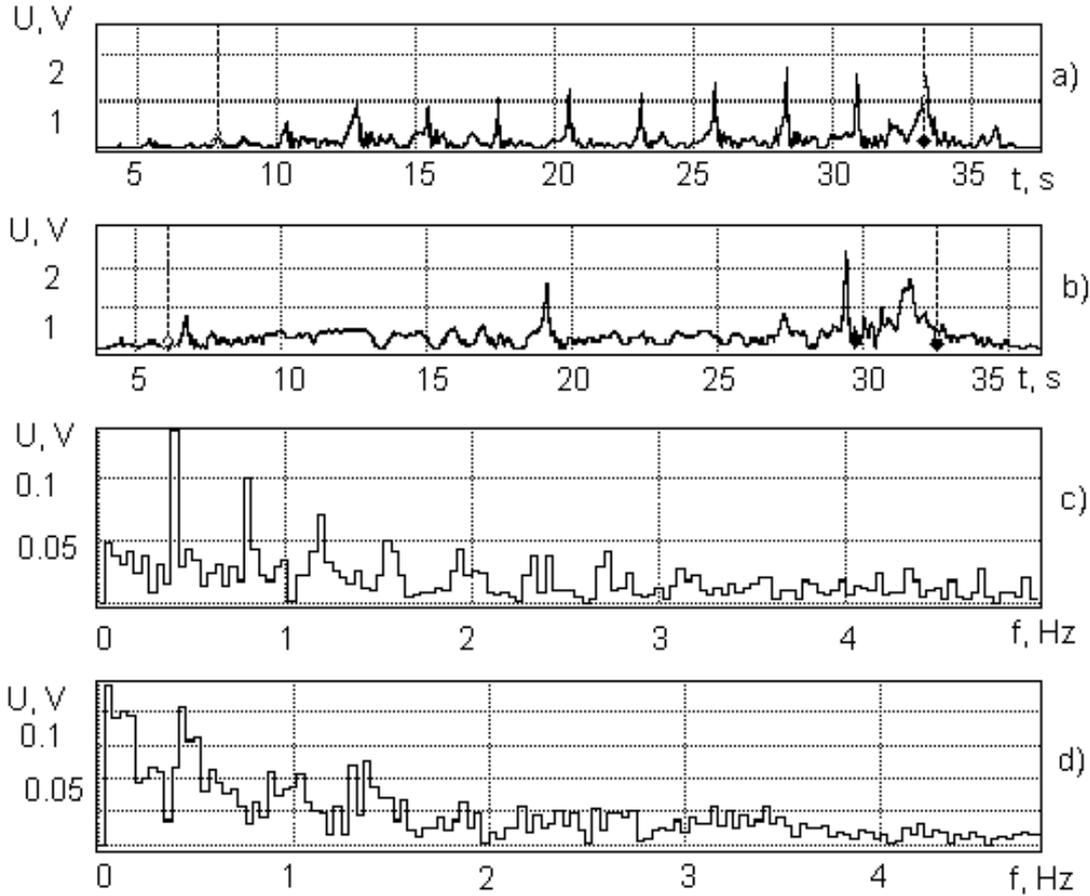

Figure 3. Inverse slopes <*S*> for curves assemblies Figure 2a - c corresponding.

3.2   Fourier analysis

  Longitudinal waves are exciting in water, when the pipe is filled with it. They damp some Lamb waves resonance in the wall. But some of them didn't undergo the changes and form the beginning of the correlation functions without changes. The method with Fourier transformation as seen in the Figure 4 is more sensible. Because of the different spectra, empty - dry and filled with water pipes can be recognized.

  The FFT was made between markers (Figure 4a and 4b). Resonance peaks periodicity must be ensured carrying out AFCh. This can be ensured only till the certain boundary, because used waves have considerable dispersion. It may be nessesary to choose the frequency changing law inverse according the dispersion law.

  On the other hand, the peak periodicity is not important while counting AFCh correlation function, only the characteristics of function F_r maximums depend on it. These maximums are obtained when the difference of f_{m+i} and f_m is equal to the interval between two AFCh maximums, i.e. when the maximums of the both multiplicands of the equation (2) coincide, where the second multiplicand is moved $U(f_m)$ i.e. $U(f_{m+i})$. Its later maximums are not important for measurements using function F_r till the first minimum.

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Figure 4. The AFCh of empty pipe (curve a) and pipe filled with water (b), displayed as time function, and its spectrum (c and d).

3.3 Investigation of transient response

The waves are formed in each point by switching the exciting as a superposition of the partial waves. The first received wave is propagating along the shortest way (mostly geodesic line) from exciting to receiving point. Each other goes as far as 1, 2, 3, … and more rotations. They all form the transient response.

At each moment of the time the wave $\vec{u}$ in receiving point can be imagined as a phasor $\vec{u}$ - vector sum of the first wave $\vec{u}_0$ and all waves $\vec{u}_i$ rotated 1, 2, 3, …, n-1, n times:

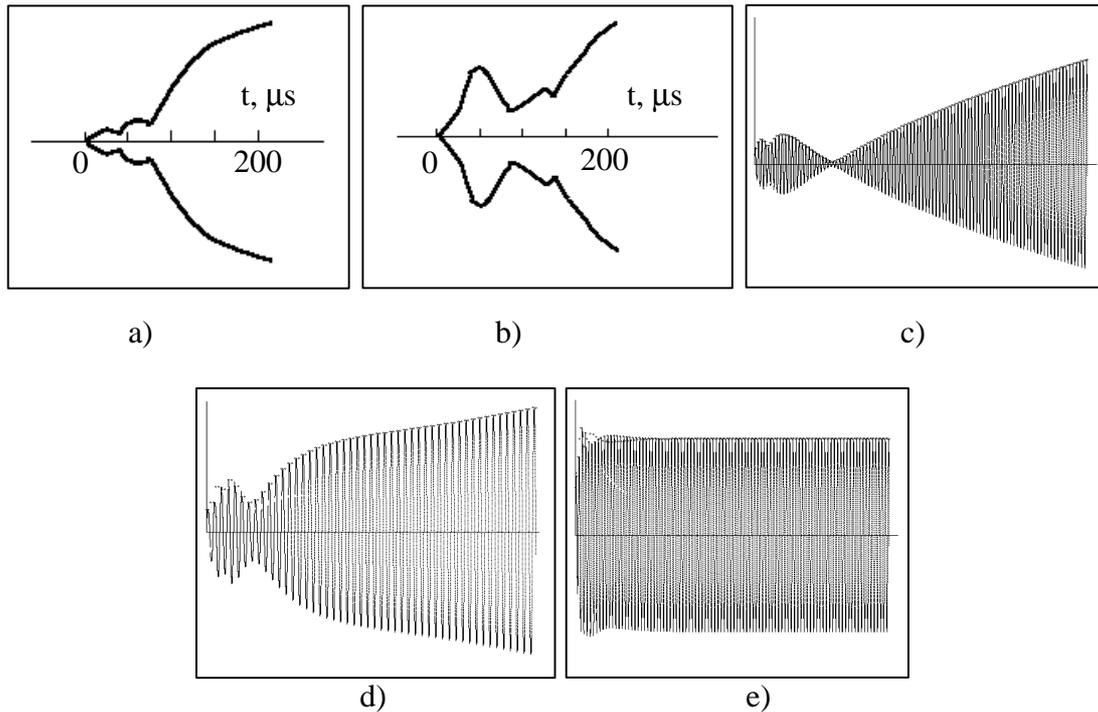$$\vec{u} = \vec{u}_0 + \sum_{i-1}^{n} \vec{u}_i \qquad (5)$$

Such wave exists from receiving the wave rotated n time till receiving the wave rotated n+1 time.

PC simulation and experiments demonstrate the transient response dependency upon the geometry of exciting and receiving. The following cases were tested experimentally: exiting of the lower transducer right shown in Figure 1 (transient response - Figure 5a), exiting the lower transducer left (Figure 5b). Both cases are simulated by PC (Figure 5c and d), also the exiting of both lower transducers in opposite phases (Figure 5e). Upper transducer receives the waves all times. We see the great changes of the transient response, especially its beginning. In such way the diagnosis of unevenness between transducers is possible.

The outer diameter of the steel pipe was 48 mm, wall thickness - 2 mm, the shortest distance between transmitting – receiving points – 8.95 λ, the perimeter was equal 6 λ, where λ - wavelength, frequency –106.6 kHz.

The differences between simulated and measured curves near minimum of the covering curve may have following reason. Our transducers have a line - form contact with pipe (the touching between plane surface and cylinder) instead point - form.

Such simulating may also be useful by developing different ultrasound equipment: delay lines, sources of the special form pulses etc.

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Figure 5. Measured (a, b) and simulated (c - e) transient responses: a - excited lower right transducer, b - lower left, c and d - that some simulated, e - excited both transducers.

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