Low-Frequency Acoustic Signals Propagation in Buried Pipelines

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Abstract. The article deals with the issues concerning acoustic signals propagation in the large-diameter oil pipelines caused by mechanical action on the pipe body. Various mechanisms of signals attenuation are discussed. It is shown that the calculation of the attenuation caused only by internal energy loss, i.e, the presence of viscosity, thermal conductivity and liquid pipeline wall friction lead to low results. The results of experimental studies, carried out using the existing pipeline with a diameter of 1200 mm. are shown. It is experimentally proved that the main mechanism of signal attenuation is the energy emission into the environment. The numerical values of attenuation coefficients that are 0,14- 0.18 dB/m for the pipeline of 1200 mm in diameter, in the frequency range from 50 Hz to 500 Hz, are determined.

1.Introduction

Recently, basic research in the field of acoustic leak detection were aimed at the solution of the problems related to the study of the characteristics of signal propagation, mainly, to the study of the field mode structure, as well as the tasks, designed to improve the localization curacy. So, theoretical study of waveguide modes propagation in buried pipelines with liquid was conducted, phase velocities, spectra and modes energy distribution in the pipeline were calculated in [1–3]. The theoretical results, obtained in [3], concerning AE signals propagation in plastic pipes are experimentally proved in [4]. For effective AE signals extraction from noise an algorithm of using Wavelet transformation is proposed in the paper [5]. In [6–8] various ways of increasing the accuracy of leakage localization using cross-correlation method are considered.

The aim of this work is to study low-frequency acoustic signals propagation in the pipes with liquid and an estimation of signal attenuation. Also, the studies could be useful in development of long-range detection equipment for inline objects (pigs), which are moving with the flow of the pumped liquid.

Already published papers concerning the study of sound attenuation in the pipes deal with consideration of the attenuation in the frequency range from 10 to 100 kHz. From [9] it is known that for the majority of liquids in a wide range of frequencies there is a quadratic dependence of the sound attenuation coefficient on frequency. However, according to [10] attenuation coefficients, measured using a real pipeline in the frequency range of 10–50 kHz, are accurately approximated by a linear dependence. The values, obtained in [10], significantly exceed theoretically calculated attenuation coefficients, caused by the presence of viscosity, thermal conductivity and liquid pipe wall friction.

Paper [1] shows that using the numerical solution of the equations of hydrodynamics and dynamic elasticity theory for a three-layer waveguide: pumped liquid - a pipeline wall – soil, under certain conditions, in addition to signal attenuation due to internal losses, acoustic signals could be attenuated by energy emission into external environment. Nowadays, there are no accurate analytical and numerical solutions to estimate the signal attenuation caused by emission during its propagation in complex three-layer waveguide. However, there is a number of works devoted to the cylindrical shell sound emission in simpler conditions [11–13]. For example, [13] shows theoretically and experimentally that the cylindrical shell emitted power increases with increasing shell diameter, whereas emission coefficient in the low frequency region increases with increasing frequency. In authors' point of view, these regularities will be implemented during signals propagation in complex layered medium, but quantitative assessment of the ratios, obtained in these papers, will give incorrect results.

2.Experimental installation

The scheme of carrying out research on excitation and propagation of acoustic signals is shown in figure 1. The main element of this scheme is the section of the trunk pipeline with a diameter of 1220 mm and a wall thickness of 15.2 mm. This is the maximum diameter of the pipeline, used for oil transportation. Pipeline construction is made in accordance with Russian formal building regulations. The pipe is filled with West Siberian oil, which was moving at a velocity of 0.85 m/s.
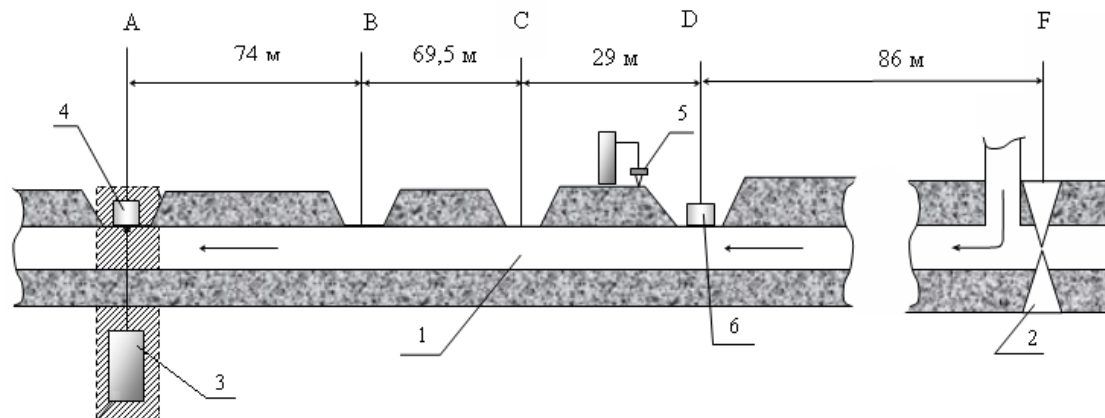
Figure 1. The scheme of research of low-frequency acoustic signals propagation using operating pipeline: 1 – pipeline; 2 – pipe valve; 3 – an electric signal generator; 4 – emitter; 5, 6 – receiving transducers; A, B, C, D – pits; F – pipe valves.

For direct access to the pipe, the areas without soil cover (pits) were kept. The insulation coating is reinforced film of polymeric tapes (2-layered polymeric insulating tape with 0.6 mm thickness of each and the protective wrap with a thickness of 0.6 mm). Backfilling material is watered sand. The ground water level is up to the middle of the pipe. One side of the pipeline section had a pipe valve and pipe rotating is 90^0, the other side had the closest valve at the distance of 4.0 km away. The pressure in the pipe during the testing period was 1.7 MPa.

Acoustic vibrations were excited using the emitter of the electromagnetic type, developed by the authors. Signals recording was carried out using two transducers of different types: electrodynamic type transducer (CV-10C brand), industrially manufactured, and the piezoelectric transducer, developed by the authors. Industrially produced receiving transducer CV-10C has the following characteristics: natural frequency is 10 Hz; the second resonance frequency is 70Hz; conversion factor is 18 V·m^{-1}sec. The ohmic resistance of the inductance coil is 285 Ohms. Piezoelectric transducer, developed by the authors, has the frequency range from 5 to 2000 Hz and sensitivity of 100–150 mkV·Pa^{-1}.

Receiving transducers were installed on the pipe wall directly through the insulation film layer or on the soil near the pipeline.

The signal from piezotranducers output goes to the preamplifier. Noise level of the amplifier, given to the input, in the frequency band 1 kHz, did not exceed 0.3 mV. Voltage amplification gain was 10 (20dB). The signal from the preamplifier output went to a recording device.

## 3. Experimental results and their discussion

During the research receiving transducer was installed on the pipe wall (figure 1) in D pit, and an acoustic signal emitter with the generator were alternately installed in pits C, B and A. In addition, single impulses were emitted into the pipe with a frequency range from a few hertz to a few kilohertz.

Several ways to receive the signal at a fixed distance from the emitter were tested: from clean pipeline wall, without the acoustic contact lubricant; from pipeline wall with contact lubricant; through 2-layered film insulation without contact lubricant; through 2-layered film insulation with contact lubricant. In all these cases, we did not observe any significant change in the signal amplitude or a phase. Therefore, later, receiving transducer was installed on the pipe through two-layered film insulation without lubricant.

Oscillogram and calculated with their use frequency spectrums, obtained in the tests under the contact signal input at the probing signal emitter location in the pits C, B and A, are shown in figures 2, 3.
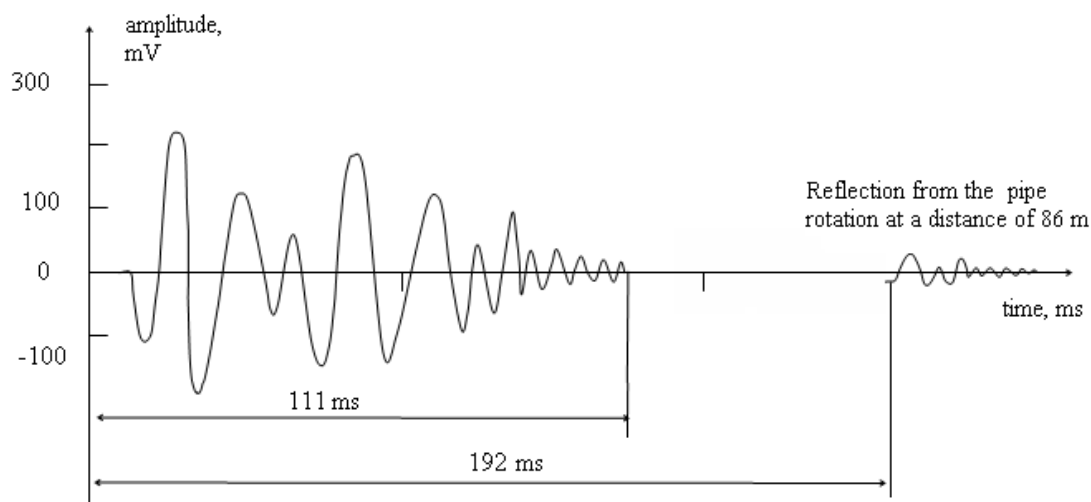
Figure 2. Oscillogram of the signal when the emitter is far from the receiving transducer in 29 m.
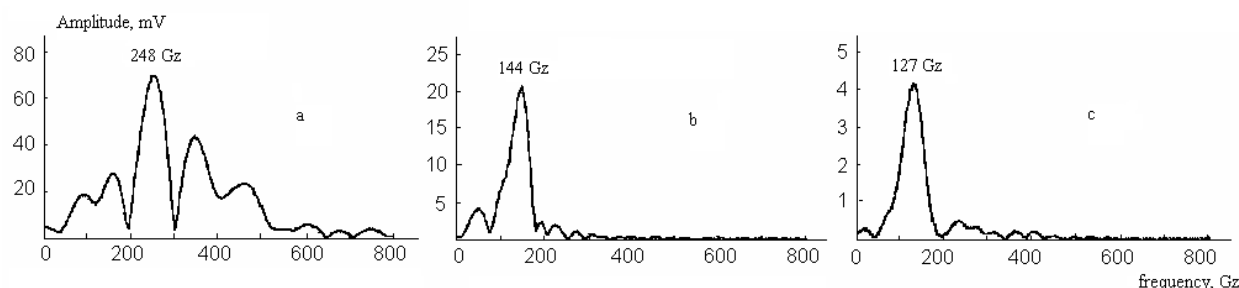
Figure 3. Frequency spectrum of sounding signal at different distances between the emitter and the receiving transducer (a–29 m, b–98.5 m, c–72.5 m).

When the emitter is located in B and C pits, there are the cases of signal reflection from the valve F (figure 2). It helps to estimate the velocity of signal propagation

$$V = \frac{2S}{\Delta t} = \frac{86 \times 2}{(192 - 27.4) \times 10^{-3}} = 1045 \text{, m/sec}$$

Where S is the distance from receiving transducer to the valve, m.

The value of the obtained sound speed matches with the speed of the pressure wave, obtained using well-known Korteweg equation:

$$c = \sqrt{\frac{K}{\rho}} \left(\sqrt{1 + \frac{Kd}{E\delta}} \right)^{-1} = \sqrt{\frac{1.35 \cdot 10^9}{810}} \left(\sqrt{1 + \frac{1.35 \cdot 10^9 \cdot 1.2}{2 \cdot 10^{11} \cdot 0.0152}} \right)^{-1} = 1042.8 \text{, m/sec}$$

Where K – liquid (oil) cubic elasticity modulus – $1.35 \cdot 10^9$ Pa; E – pipe (steel) material elasticity modulus – $2.0 \cdot 10^{11}$ Pa; ρ – liquid (oil) density–810 kg/m^3; d, δ – inner diameter and 1.2 m. and 0.0152 m. pipes wall thickness, respectively.

Fitting calculated and experimentally measured velocities proves that the acoustic signals in the pipe are spreading along the liquid. The Signals with other propagation velocities were not observed.

Figure 3 shows that the oil pipe, while transmitting low frequency acoustic oscillations, behaves itself as a low-frequency filter. This could be seen if comparing the frequency characteristics of the signals. When the emitter was located in C pits (figure 3a 29 m. distance) 248 Hz $\pm \Delta F$ components prevailed in the frequency spectrum, but at emitter position in A and B pits (the distance is 172.5m and 98.5m) these components are already absent. This is in accordance with published theoretical and experimental results concerning stronger attenuation of high-frequency signals.

For determination of the acoustic power introduced into the pipe, it is necessary to determine the acoustic power, detected with the transducer at the distances of 29, 98.5 and 172.5 m. from the emitter, and, then, to approximate obtained values at the point of pipe signal input. In this case, the wave in the pipe is considered to be flat, and pipeline wall to be thin. Taking that into account, the pressure, detected with the transducer on the outer pipe wall, will be taken equal to the pressure of the liquid inside it. Instantaneous intensity of acoustic wave (instantaneous flow density of power) is determined by the known ratio [9]:

$$I(t) = (\rho c)^{-1} p(t)^2, \tag{1}$$

Instantaneous intensity is connected with acoustic power by equation:

$$P_x = \frac{1}{T} \int_0^T \int_S I(t) dt ds = \frac{1}{\rho c T} \int_0^T \int_S p(t)^2 dt ds \tag{2}$$

While integrating (2) over time and area, believing that a wave is flat, for the acoustic power at x distance from the emitter we get

$$P_x = \frac{\pi R^2}{\rho c T} \int_0^T p(t)^2 dt = \frac{\pi R^2}{\rho c T} (\gamma K_u)^{-2} \int_0^T U(t)^2 dt \tag{3}$$

where ρ–density of liquid, c–sound velocity in liquid; R – pipeline radius; T – duration of pressure impulse; γ – transducer sensitivity (in our case, 100–150 mkV/Pa); K_u– preamplifier voltage amplification gain; $U(t)$ – receiving transducer voltage dependence on time.

Substituting in equation (3) the following parameters $R = 0.6$ m; $c = 1045$m/s; $\rho = 810$kg/m3; $K_u = 10$; $\gamma = 10^{-4}$ V/Pa; and integrating numerically voltage dependences shown in figure 3, as a the result, we get the following values of acoustic power at the distances of 29, 98.5 and 172.5 meters from the emitter:

$P_{29}= 77.75$ mW; $P_{98,5}= 5.91$ mW; $P_{172,5}= 0.26$ mW;

Approximating the data with a cubic spline interpolation, we get the following values of acoustic power at the pipe signal input: $P_0=140.46$ mW

Integral attenuation coefficients by signal power are found using the equation

$$\alpha = \left| \frac{10 \lg(P_{s1}/P_{s2})}{s1 - s2} \right| , \text{dB/m} \tag{4}$$

where *s1*, *s2* – distances from the emitter to input point. Calculated results based on the equation (4) are shown in the Table 1.

Table 1. Experimentally obtained attenuation coefficients of low-frequency pipeline signals

s1–s2	69.5	74	143.5	172.5	98.5	29
α, dB/m	0.16	0.18	0.17	0.16	0.14	0.089

Table 1 shows that the attenuation coefficients, obtained using experimental data (the first three points) have similar values, the difference is 0.01 dB / m (~ 6%). Approximately, the same values are obtained using the calculation based on the approximated value of the acoustic power at the pipe signal input point (the last point has the largest diversity, which is caused by approximation error).

This suggests that the resulting P_0 value corresponds approximately to the real power introduced into the pipe. In this case, factor of electrical power conversion into acoustic power is $\eta = (140.46 \cdot 10^{-3})/860 = 1.6 \cdot 10^{-4}$

The calculations show that at mechanical strike a small part of the energy is transformed into acoustic signal energy, which can be detected on the external pipeline wall. Probably, the main striking energy is transformed into waves energy, that are reflected from the outer and inner pipeline walls and do not penetrate the pipeline inside.

At the strike from the pipeline internal side, it could be expected that the main striking energy will be concentrated inside the pipeline, but because of the large acoustic impedances difference of the pipe wall and pumped liquid, only a small part of the energy will be transformed into waves, detected from the outside. More accurate value of the conversion factor can be obtained by solving the three-dimensional equations of cylindrical shell moving and the hydrodynamic equations.

To check the signal attenuation caused by energy emission into the soil, receiving transducer was installed on the pipe through the soil layer, and, then, was removed from the pipe axis along the soil surface. Measurements were carried out at the emitter position at B point (100m). The disappearance of the signal was observed only at receiving transducer location at the distance of more than 10m from the pipeline axis.

While approaching to the pipe, the signal increases to a maximum above the pipeline axis. In this case, signal delay dramatically increases compared with that, occurred at the receiving transducer location on the pipe wall. When installing the sounding emitter in C pit (29m), active area around the pipe increases up to 12–13m. In this case, only one signal was caught by recording device. This shows that the signal, propagating through the pipeline, emits an acoustic energy into the environment (into the soil), which, in authors' opinion, is a reason of high signal attenuation.

References
[1] Lapshin B M, Ovchinnikov A L (1998) Examination of the propagation of elastic waves in pipes with a liquid in acoustic emission leak testing *Russian Journal of Nondestructive Testing* **34** (7) 494–500
[2] Long R, Cawley P, Lowe M (2003) Acoustic wave propagation in buried iron water pipes *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **459**(2039) 2749–2770
[3] Muggleton J M, Brennan M J, Pinnington R J (2002) Wavenumber prediction of waves in buried pipes for water leak detection *Journal of Sound and Vibration* **249**(5) 939–954
[4] Muggleton J M, Brennan M J, Linford P W (2004) Axisymmetric wave propagation in fluid-filled pipes: Wavenumber measurements in in vacuo and buried pipes *Journal of Sound and Vibration* **270**(1) 171–190
[5] Ahadi M, Bakhtiar M S (2010) Leak detection in water-filled plastic pipes through the application of tuned wavelet transforms to Acoustic Emission signals *Applied Acoustics* **71** (7) 634–639

[6] Gao Y, Brennan M J, Joseph P F (2009) On the effects of reflections on time delay estimation for leak detection in buried plastic water pipes *Journal of Sound and Vibration* **325**(3) 649–663

[7] Lapshin B M, Ovchinnikov A L, Chekalin A S (2011) Features of the search for leaks in pipelines of heat networks using the acoustic-emission method *Russian Journal of Nondestructive Testing* **47**(10) 710–717

[8] Ozevin D, Harding J (2012) Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity *International Journal of Pressure Vessels and Piping* **92**(4) 63–69

[9] Golyamina I P 1979 *Ultrasound: small encyclopedia* (Moscow, Sov. Encycl.)

[10] Nikolaeva E D 1991 *Development of acoustic emission method of continuous control of underwater pipelines tightness: PhD. thes*. (Tomsk, NDT SRI, TPU)

[11] Vovk I V (1982) Radiation of sound by coaxial cylindrical shells *Akusticheskij Zhurnal* **28**(4) 470–473

[12] Kremleva O A, Shkundin S Z (1998) A method for calculating acoustic fields in a finite cylindrical channel with a flow *Acoustic Journal* **44**(1) 84–88

[13] Retling E V (2012) Concerning acoustic radiation of a cylindrical shell *VolgGASU Internet-series. Ser .: Polythematic* **1**(20) 1–6