Geolocation and diagnostics of trunk pipelines using an active acoustic sensor

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Abstract. The article discusses the issue of determining the location of the main pipeline to identify the deviation of its position from the design due to climatic factors. The possibility of using active sensors capable of operating both as diagnostic devices installed on the main pipeline and as a beacon is investigated, according to the signal of which it is possible to determine the location of this sensor with acceptable accuracy. The optimal operating frequencies are determined by mathematical modeling to ensure the maximum data transfer rate and the required signal-to-noise ratio. The simulation results show the possibility of assessing the attenuation of signals in the ground, as well as determining the limiting range of the method.

1. Introduction
Geolocation of main pipelines is an urgent task for monitoring strategically important facilities that require registration of displacements of location from the design one. Periodic monitoring makes it possible to detect deformation of the pipeline due to soil subsidence caused by thawing and freezing, which entails soil displacement, creating a stress-strain state (SSS) of the pipeline. SSS, in turn, can lead to damage to the pipeline, spillage of the transported liquid or an unpredictable release of the gas mixture.

Today, the diagnostics of main pipelines has a sufficient number of geo-location methods [1-3]. The closest to the developed positioning method is the in-line diagnostics method. This method, when using an inline inspection tool (IIT), allows you to obtain information about the state of the pipeline and its position. The position of the pipeline when using in-line diagnostics is determined using a strapdown inertial navigation system (SINS) installed on the IIT [4]. However, the main task of the system - projectile orientation - high accuracy - is not solved due to the low accuracy of autonomous SINS.

Existing methods of subsurface geolocation:

1. Method of magnetic location. The technical implementation of magnetic location is based on solving the inverse problem of magnetostatics - spatial search for an object and determining its parameters based on the results of measuring the magnetic field vector in a finite number of points in space at a considerable distance from the object [5].

2. The magnetometer method is based on the measurement of the magnetic field vector. In most cases, the magnetometer sensor consists of three magneto-sensitive transducers. Each of the transducers measures the projection of the magnetic field induction onto its sensitive axis [5, 6, 8, 10].
3. Acoustic location. Acoustic methods are most widely used when searching for water in underground pipelines. A variation of this method is widely used for tracing underground water pipelines, especially plastic pipelines [7].

4. Infrared thermography. The temperature of buried pipelines can be different from the temperature of the surrounding ground. Determination of the temperature difference can be a fairly effective method for locating underground pipelines [9], however, this method has not yet received industrial distribution due to a number of limiting factors.

The proposed method of geolocation of main pipelines is based on the use of an active sensor installed on the pipeline at the stage of laying the pipeline, which is activated by an external device during a periodic diagnostic inspection. The installed sensor is able to read the natural vibrations of the pipeline to detect changes in the spectral component of the natural vibrations of the pipeline, with the subsequent transmission of the collected data to the surface via a radio channel with a reader that activates the sensor and receives data from it, which, in turn, is used to determine the location of the sensor. Installed on the pipeline, and for the technical condition of the pipeline.

2. Method and materials
The general model of the distribution environment has dimensions of 10 \times 20 \times 8 \text{ m}, includes an air layer 4 \text{ m} high and a soil layer with parameters \((\sigma=5\times10^{-2}, \mu=1, \varepsilon_r=15)\), which corresponds to a soil layer of average moisture. At a depth of 1.5 \text{ m} in the ground, there is a pipe with a diameter of 1 \text{ m} and a wall thickness of 10 mm, the pipe material is steel without ferromagnetic properties. The pipe cavity is filled with gas with the electrophysical properties of air. At a height of 2 \text{ m} above the ground in the air, there is a transmitting antenna in the form of a copper coil on a ferrite core.

In the process of modeling the communication channel "from top to bottom", the following parameters of the transmitting coil were used to activate the sensor installed on the pipeline: \(\mu_{\text{cep}} = 700\), wire diameter \(d = 1.4 \text{ mm}\), core radius \(R = 25 \text{ mm}\), core length \(l = 200 \text{ mm}\), number of turns \(N = 100\), antenna current \(I = 100 \text{ mA}\).

Model studies were carried out on the basis of the finite element method, which consists in dividing the computational domain into many elements and numerically solving Maxwell's equations connecting electric and magnetic fields with the vector field potential and currents in the medium at the common nodes of these elements:

\[
\begin{align*}
rotH &= J, \\
B &= rotA, \\
J &= \sigma E + j\omega D + J_e, \\
E &= -j\omega A,
\end{align*}
\]

where \(j\omega D=J_{\text{an}}\) - displacement current; \(\sigma E=J_{\text{an}}\) - conduction current; \(J_e\) is the electric current density generated by external sources (antenna current); \(H\) is the magnetic field strength; \(E\) is the electric field strength; \(B\) - magnetic induction; \(A\) is the vector potential of the electric field; \(D\) - electrical induction; \(\sigma\) - electrical conductivity; \(J\) is the electric current density.
3. Results and discussions
The propagation of the magnetic field from the transmitting porridge is shown in figure 3. The receiving point of the signal emitted in the model was set above the pipeline. At this point, a frequency study was carried out in the range from $f = 1$ kHz to $f = 200$ kHz. Figure 4 shows the results of model experiments on recording the magnetic field level of a ferrite antenna in the area of a steel pipe under conditions of a 1.5 m layer of surface soil.
The signal was received on a compact ferrite antenna, the signal level at which can be determined by the formula [2]:

\[ U = \omega \cdot \mu_0 \cdot H_z \cdot S_{EF}, \]

where \( S_{EF} = \mu_{SER} \cdot S_{SER} \cdot n_{PR} = m^2 \) is the effective area of the receiving inductive antenna; \( \mu_{SER} = 2000 \) - magnetic permeability of the core; \( S_{SER} = 1.25 \times 10^{-7} \text{ m}^2 \) - core cross-sectional area; \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) - magnetic constant; \( n_{PR} = 4000 \) is the number of turns of the receiving antenna; \( H_z \) is the intensity of the vertical component of the magnetic field.
To analyze the return channel, the transmitting antenna was moved to a point in the immediate vicinity of the pipe surface and enclosed in a sphere of air to exclude contact with the conductive medium (soil). The air sphere simulates the body of the transmission device on the main pipeline. An analysis similar to the one presented previously was carried out.

Figure 6. Transmitting antenna in the aerial sphere underground.

Figure 7. Propagation of the magnetic field from bottom to top.
4. Conclusions
In the course of the simulation, graphs of the strength of the magnetic field created by the transmitting coil for the channel "top-down" and "bottom-up" at frequencies from $f = 1$ kHz to $f = 200$ kHz were obtained. The obtained values of the magnetic field strength made it possible to estimate the voltage level induced on the receiving antenna at the point of signal reception both on the pipeline and on the surface at a height of 2 m from the ground. Analyzing the signal level at the output of the receiving antenna, it can be concluded that the amplitude of 0.5 μV is insufficient and requires the introduction of additional engineering solutions: an increase in the equivalent area of the receiving antenna, the introduction of an amplifier stage, and an increase in the transmitter power.

The problem of determining the coordinates of a radiating sensor installed on a pipeline can be solved using spaced three-component antennas with a fixed base. The intersection of the calculated magnetic field vectors from each three-component antenna will indicate the location of the sensor relative to the receiving antennas, the coordinates of which are determined by the satellite navigation system.

The sensor being developed simultaneously solves:

1. a location task in the mode of inspection diagnostics using unmanned or guided vehicles;
2. the task of collecting diagnostic data on the state of the pipeline, based on constant measurements of the vibration level, by transferring them to the on-board data collection system of the mobile diagnostic complex.
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