A method for monitoring the violation of the integrity of pipeline communications using a radio wave vibration sensor

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Abstract. The article discusses the implementation of a continuous vibroacoustic control system, in order to detect leaks and quickly prevent emergencies, describes the principles of their functioning. The existing method of recognizing leaks is considered. The analysis of non-contact methods for measuring vibration parameters is carried out, radio wave methods are highlighted as the most promising. A non-contact radio wave vibration sensor is considered, which is introduced into the pipeline monitoring system. The proposed systems of vibroacoustic control allow one to effectively diagnose the state of the pipeline at low time costs and with a low error in detecting a useful signal. The physical and mathematical meaning of the method being introduced was also considered. The scope of application of the research results relates to industries (heat power, gas and oil fields), in which complex dynamic objects are used with the need to use a non-contact method for monitoring vibration and displacement parameters.

1. Introduction
In the modern world, very little attention is paid to diagnostics of the technical condition of pipelines. The service life of pipeline systems is sometimes more than 30 years. Over the course of this time, they are affected by many different factors, for example, natural and climatic influences, changes in pressure inside the pipes. In addition, the geographical features of the place of laying the pipes have a great influence.

All of the above factors lead to the fact that the service life of the systems is reduced and leads to a large number of leaks, the subsequent development of which can cause an emergency. This is the reason for the need for prompt and accurate identification of possible problem areas of leaks, localization of earthworks and fast reconstruction of water supply and heating networks. Since the costs of a complete replacement of pipeline systems are extremely high, long-term and not always possible, for example, pipelines under highways, it is necessary to implement pipeline monitoring systems. The main challenge is to optimize, improve the quality, reliability and safety of pipelines. To achieve this goal, it is necessary to reduce the amount of damage to the water supply network, as well as to reduce the cost of repair work. Thus, the solution to the problem of monitoring the condition and rapid response to emerging pipeline failures is important and relevant today. We consider a system for
diagnosing the state of pipeline systems using a radio wave vibration sensor and describe their effectiveness.

2. Existing method for diagnosing leaks
The most widespread defects are thinning and destruction of the integrity of the walls, which leads to metal corrosion, cracking, all of these factors lead to leakage. Detecting a defect as quickly as possible is of paramount importance, as early identification and elimination of the problem will prevent further major accidents.

These defects can be detected using a radio-wave vibration sensor, which is based on the excitation of vibroacoustic signals in the pipe shell with their subsequent diagnosis at a given area. The result of the operation of the investigated object is signaled by a sensor that provides a small amount of information about the state of the pipeline section. But the combination of such signals allows you to identify defects and assess the technical condition of the product pipeline.

Today, the principle of detecting leaks is as follows. A pair of copper conductors is located around the perimeter of the pipeline, under a thermal insulating coating. To diagnose the occurrence of leaks and determine the distance to it, the change in resistance value is measured. The low efficiency of the current method is manifested in the fact that, firstly, if a leak occurs from the reverse side of the pipe, then the short circuit of the conductors may not occur immediately after the leak appears. Secondly, shorting of conductors can occur without malfunctions. Defects on the walls of the hot water supply pipeline lead to a significant decrease in energy efficiency in case of violation of thermal insulation, and if damage is not detected for a long time, accidents are possible. At the moment, the diagnosis of such damage is not performed, because of this, their presence can be judged only by how much the ground surface over the pipeline is warming up [1].

3. Comparative analysis of sensors
To begin with, we will consider the existing types of sensors and evaluate their effectiveness for subsequent implementation into the system (Table 1).

| Duration of implementation | Optical | Ultrasonic | Radio waves |
|---------------------------|---------|------------|-------------|
| Is excavation necessary   | yes     | yes        | no          |
| Influence of natural conditions | Smoke, water vapor and dust prevent | Does not affect | Does not affect |
| Frequencies               | 0-20 MHz| 0-3000 Hz  | 0-250 kHz   |
| Working temperature       | -60 to + 60°C | -40 – 85 | -60 °C to +80 °C |
| Does it register interference | no     | no         | no          |
| Signal reading range      | 0.1-10 m| No more than 1.5-2 m | 0.2-10 m |
| Is there a possibility of replacement without destroying the integrity of the system | no | no | yes |
| Disadvantages             | Complexity, high cost of equipment; high energy consumption. | Dependence on pressure, temperature, error is possible. Low resolution, low dynamic range. | Calibration complexity (for amplitude methods) |
| Advantages                | Fire safety high precision, small size, corrosion resistance. | Suitable for pipes of any diameter. Cheapness and compactness of equipment. | Wide dynamic range, measuring poor under conditions |
When choosing sensors, we consider the following characteristics:

- Compact and sturdy mechanism that will allow for installation in certain operating conditions.
- The design should guarantee the maximum sensitivity of the fiber to various influences, depending on the conditions of use.
- The use of various types of structures in terms of materials and properties, based on the impact of environmental conditions (aggressive chemicals, high or low temperatures, crushing loads, etc.).
- The structure should be light, facilitating the installation work [2].

As shown by a comparative analysis, the most advantageous sensor is a radio wave.

4. Introduction of a radio wave vibration sensor

The leak detection method used today is not the most reliable and effective, so we will try to introduce a radio wave vibration sensor into the system. After considering existing sensors, we concluded that the radio wave vibration sensor has a low cost, while having many advantages. Among them, the possibility of measuring vibration occurring at distances inaccessible for ultrasonic measurements, at distances of more than 2 m. This makes it possible to install the sensor not too close to the pipeline, thereby not carrying out excavations, which reduces the cost of implementation (time and money for workers and equipment) (Figure 1).

Also, a significant advantage is the ability to replace it with a new observation point without dismantling or stopping the controlled object, which cannot be realized by contact sensors, since they require excavation of the pipeline to directly install or replace the sensor with them, thereby increasing the cost of additional excavations. The superiority of a radar vibration sensor over laser ones is the ability to measure vibration on an object, even if there is water vapor or other optical interference.

Also, the advantage of a radar vibration sensor is the accuracy of determining the frequency and amplitude of vibration using a sensor operating in the millimeter wavelength range, in contrast to sensors that use traditional radio bands (3-30 GHz). This is explained as follows. In order for the phase of the reflected signal at the receiver to change 360 degrees, the distance must change by half the wavelength. One and a half millimeters for a 3-mm 94 GHz sensor gives 360 degrees, and for a 3-cm 9 GHz it is only a tenth. In other words, the 94 GHz sensor turns out to be more sensitive to vibration compared to lower frequency radar wavelength ratio sensors [3].

Frequency and amplitude measurements using 1D, 2D or 3D can be used to analyze vibration parameters by taking data from vibration sensors. For this, it is necessary to introduce, respectively, 1, 2, or 3 radar vibration sensors [4].

Since vibration measurement can take place at a distance of more than two meters, the installation of the sensor does not take place too close to the pipeline, which makes it possible to reduce the cost of implementation, since you will not need to carry out large-scale excavations to install it.

5. The physical meaning of the radio wave method

Radio wave measurement methods are based on the use of dependencies on the controlled value of various parameters of electromagnetic systems used as primary measuring transducers. These parameters include: the amplitude and phase of the reflected signal; frequency of electromagnetic oscillations of the system, its quality factor; the number of excited types of oscillations; transit time of an electromagnetic wave from a radiation source to a controlled object, etc. In radio wave methods, 2 groups are distinguished.

Resonator. To work with indicators, the device, the degree of vibration of which must be determined, is placed in the region of the microwave resonator, which ensures their small error. The disadvantage here is a complex design, without the possibility of diagnosing at long distances, a rather complex presentation of the study of the data obtained, which, as a result, does not allow them to be used in many areas of industry [5].
Interference is using microwave sounding, in their subsequent consideration in reflection from an obstacle. Due to interference and electromagnetic influences, a standing wave appears, which changes its amplitude under the influence of vibrations.

In the head of the radio wave vibration sensor we have considered, there is an interference radio wave method for assessing the phase of the reflected signal. Vibration of the sensor leads to phase and amplitude modulation of the reflected wave, and subsequently to the formation of a beat signal. As a consequence, the phase of the reflected signal includes all information about the vibration characteristics of the object under study.

One of the main advantages of the phase method is that the amplitude of the reflected signal is not used in the calculation of vibration parameters. This made it possible to invent an intelligent sensor that can operate at a long distance to the pipeline, with high metrological characteristics and unified analog and digital interfaces [6].

The economic efficiency of such a sensor is that there is no need to carry out large-scale excavations for its implementation or replacement in the pipeline system, which significantly reduces the cost of implementing this method.

The sensor measures such parameter as vibration velocity. This characteristic shows the power of the oscillatory (vibration) process [7]:

$$V = 2\pi fS,$$

where $f$ is the vibration frequency, which helps to identify the vibration source; $S$ – value of vibration displacement.

The structure of the radio-wave vibration sensor is considered below (Figure 2).

The vibrometer includes a transceiver module (TCM), an analog signal input-output module (ASIOM) and a personal computer (PC).
TCM contains a generator of EHF range, directional coupler H01, with the help of which the measuring and reference channels are formed, phase manipulator M, which provides phase modulation of the probing signal with a signal of intermediate frequency $f_{IF}$. The horn antenna A is both receiving and transmitting; directional coupler H02, which selects EHF waves reflected from the measurement object. A balanced BS mixer, in which the interference of the modulated reflected signals with the unmodulated reference signals is carried out and at its outputs the Q and I quadrature signals of the intermediate frequency, carrying information about the phase of the signal and, therefore, about the vibration parameters, are extracted (Figure 2).

A two-channel analog-to-digital converter is part of the MVVAS structure, which provides the ability to change the Q and I quadrature signals of the intermediate frequency into digital form and transfer them to a PC, a digital-to-analog converter that processes the baseband $f_{IF}$ signal, a pulse generator $f_{ADC}$, $f_{DAC}$ that clocks the operation of the ADC and DAC. In the PC, processes are performed using mathematical processing of incoming signals, calculation and determination of the deviation of the measured vibration parameters [8].

6. The mathematical meaning of the radio wave method

The following mathematical model of quadrature signals is used to determine vibration parameters by the radio-wave phase method (Figure 3).

From the phase value and the known wavelength of the probing signal $\lambda$, it is easy to calculate (1) the instantaneous value of the displacement $D(t)$ and determine the vibration parameters:

$$Q = X(t) = A \cos(\phi(t)), \quad (2)$$
$$I = Y(t) = A \sin(\phi(t)), \quad (3)$$

where $\phi(t)$ is the instantaneous value of the phase of the reflected signal associated with the displacement $D(t)$ of the object surface by the ratio:

$$\phi(t) = (D(t)4\pi/\lambda), \quad (4)$$

where $\lambda$ is the wavelength of the probe signal.

We calculate the phase from the values of the quadratures as follows:

$$\phi(t) = \arctg(Y(t)/X(t)). \quad (5)$$
Based on the presented phase method with the introduction of modern digital signal processing, a non-contact radio wave vibration sensor has been created that operates at a long distance to the pipeline, vibration amplitudes, frequencies and displacements, characterized by high metrological properties, unified analog and digital interfaces. The radio wave vibration sensor belongs to a new generation of sensors designed for continuous remote monitoring of dynamic and static characteristics of structural elements of any source.

Based on the foregoing, we can say that an intelligent sensor is a sensor that performs the functions that are mandatory for the implementation of an accurate description and provision of the measured value. In addition to self-testing, the sensor performs such functions as measuring, ordering and correcting the signal we receive. An individual quality of a contactless intelligent vibration sensor is digital signal processing immediately from the output of the initial transducer. This ensures the correctness and stability of its properties in the permissible measurement range, as well as low sensitivity to external interference.

To ensure the implementation of various functions of changing the controlled values, which can further improve the properties of the realized processes in the sensor, digital signal processing is used, including the possibility of improving the software.

For each value we determine vibration displacement, vibration velocity and vibration acceleration, statistical and spectral analysis is performed, based on which the average value, root mean square value, minimum and maximum values, swing and amplitude spectrum are determined. The characteristic property of the sensor is to provide monitoring of vibration changes from 0 Hz, which provides the function of a non-contact micrometer, as well as to perform low-error assessment of low-frequency vibrations.

7. Conclusion
As a result of the study, the authors substantiated the need for the introduction of a radio wave vibration sensor into the monitoring system of pipeline communications. A method for determining the vibration velocity of a radio wave signal reflected from an object is considered, and its mathematical model is described. The most effective sensor for the existing system has been identified, which gives an idea of the capabilities of radio wave devices and its effective application in practice.
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