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FEATURES OF THE DEVELOPMENT OF A SEARCH SYSTEM FOR TECHNOLOGICAL OBJECTS OF OIL PIPELINE TRANSPORT

مميزات تطوير نظام البحث عن الأغراض التكنولوجية لنقل خطوط الأنابيب النفطية

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ABSTRACT

The study investigated the structure and operating principle of a search device designed for intra-pipe technological objects used in oil pipeline transportation. Precise detection of the position of intra-pipe devices on the Earth's surface above an underground oil pipeline allows performing technological operations with minimal costs. The solution to the problem of developing a direction-finding device based on the sum-difference method for determining the location of an in-line technological object using a system of magnetic antennas (locators) located in the ground-based unit and a magnetic transmitter installed in the in-line device is considered. A computational experiment was conducted, as well as modelling, assembly, and testing of the search device. Parameters for optimal positioning of locators were determined to solve the task of finding the distance to the point in the pipeline where the in-line technological object is located.

Keywords: Search device, Uunderground oil pipeline, Intra-pipe technological object, Intra-pipe technological device, Magnetic antenna, Locator, Transmitter, Direction-finding, Sum-difference method.

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ملخص البحث:

تناولت الدراسة دراسة بنية ومبدأ تشغيل جهاز بحث مصمم للأجسام التكنولوجية داخل الأنابيب المستخدمة في نقل خطوط الأنابيب النفطية. يتيح الكشف الدقيق عن موضع الأجهزة داخل الأنابيب على سطح الأرض فوق خط أنابيب النفط تحت الأرض إجراء العمليات التكنولوجية بأقل تكلفة. تم النظر في حل مشكلة تطوير جهاز تحديد الاتجاه بناءً على طريقة الفرق المجموع لتحديد موقع جسم تكنولوجي خطي باستخدام نظام هوائيات مغناطيسية (محددات) موجودة في الوحدة الأرضية وجهاز إرسال مغناطيسي مثبت في الجهاز الخطي. تم إجراء تجربة حسابية، بالإضافة إلى نمذجة وتجميع واختبار جهاز البحث. تم تحديد معلمات الوضع الأمثل للمحددات لحل مهمة إيجاد المسافة إلى النقطة في خط الأنابيب حيث يوجد الجسم التكنولوجي الخطي.

الكلمات المفتاحية: جهاز البحث، خط أنابيب النفط تحت الأرض، كائن تكنولوجي داخل الأنبوب، جهاز تكنولوجي داخل الأنبوب، هوائي مغناطيسي، محدد، جهاز إرسال، تحديد الاتجاه، طريقة الفرق المجموع.

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I. Introduction

The development of efficient oil pipeline transport is crucial for sustaining the global energy supply chain. As oil remains one of the most vital energy resources, the need for effective management and monitoring of pipeline infrastructure has become increasingly significant. A search system designed specifically for technological objects within this domain can enhance operational efficiency, safety, and environmental protection.

Modern oil pipeline systems are extensive and complex, often spanning vast geographical areas. This complexity necessitates a robust search system that can effectively manage and retrieve data related to various technological objects, including pipelines, pumps, valves, and monitoring equipment. Such a system can facilitate real-time decision-making, improve maintenance scheduling, and reduce the risk of accidents.

Recent advancements in information technology, particularly in data management and artificial intelligence, have opened new avenues for developing sophisticated search systems tailored to the unique requirements of oil pipeline transport. These systems can leverage large datasets to provide insights into pipeline performance, detect anomalies, and predict potential failures, thus enhancing the overall reliability of the transport network.

Understanding the features and functionalities necessary for an effective search system is critical for addressing the challenges faced by the oil industry today. This paper aims to explore the specific requirements for developing a search system for technological objects in oil pipeline transport, emphasizing its role in optimizing operations and ensuring safety.

II. Results & Discussion

The operational principle of the search system for intra-pipe technological devices (ITDs) in oil pipelines is illustrated in Figure 1. This search system comprises two main subsystems: 1) the intra-pipe device (ID), which is positioned directly on the ITD and transmits a direction-finding signal using a transmitter; and 2) the ground device (GD).

A distinctive feature of the ground device is its inclusion of two identical receiving modules, known as locators, each housed separately. These locators continuously capture a low-frequency direction-finding signal, generated as an alternating magnetic flux from the transmitter located within the pipe device. Once received, the signals undergo scaling and filtering before being processed by the microcontroller module of the ground device. The processed signals are then displayed on a local indicator and transmitted through a wireless communication channel (WiFi) to a remote indicator, which is accessible via a tablet or Android/iOS device. This setup

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facilitates real-time monitoring and improves the efficiency of locating technological devices within the pipeline.

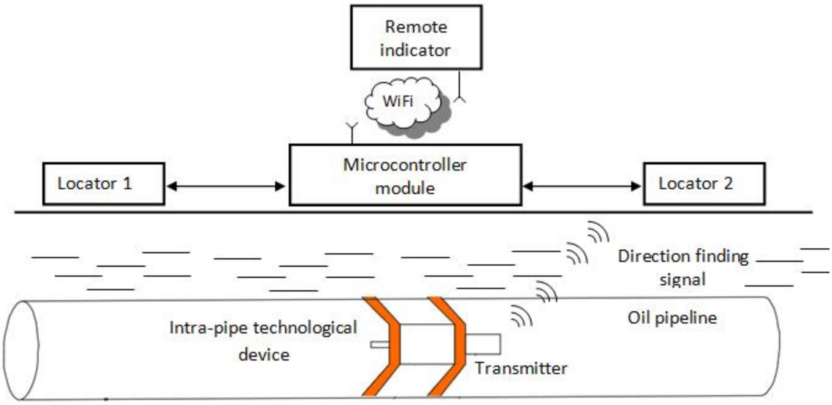

Figure 1 – The principle of operation of the search system for in-pipe technological devices of the oil pipeline

The locators are securely connected by a horizontal support rod, which houses the necessary wire connections, including power conductors and measuring lines. This rod, along with the locators (magnetic antennas), is positioned on the ground surface directly above the oil pipeline, aligned with the expected location of the intra-pipe object. By analyzing and processing the direction-finding signals transmitted from the locators to the receiver-indicator, the operator can accurately determine the position of the intra-pipe technological device. The geometry involved in locating these intra-pipeline devices for oil transport is depicted in Figure 2.

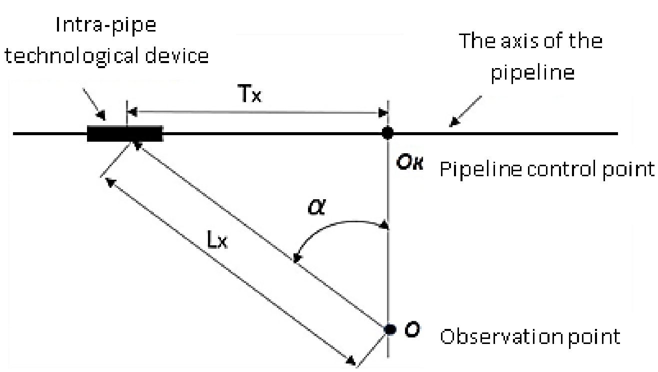

Figure 2 – Geometry of the task of finding an intra-pipe technical device: Lx – distance to the ITD from points and observation O (location of magnetic antennas); α – the angle of the direction to the ITD from the observation point O; Thx is the distance to the ITD along the axis of the pipeline T from the control point Ok.

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The inclusion of two receiving magnetic antennas (magnetic receivers) enables the determination of the location of the intra-pipe technological device (ITD) within the pipeline using a single-pulse method of direction finding in a single plane [1, 2, 8, 12].

Three known methods of direction finding are the phase, amplitude, and sum-differential methods. The phase method is impractical for locating the ITD because, at operational frequencies (ranging from 10 to 30 Hz), the two magnetic antennas, separated by a distance L, λ when (L that is much smaller than the wavelength and λ, produce nearly identical phase diagrams).

In amplitude direction finding, particularly in monopulse systems, the angular coordinate of the direction to the signal source is determined by forming two crossed directional diagrams (DD) of the antennas, separated by an angle of $\pm\alpha_0$ relative to the equisignal direction (RSD). This method requires equal and stable gain coefficients across channels; otherwise, the zero of the bearing characteristics may shift. To minimize the dependence of the direction-finding characteristics on signal levels, logarithmic amplifiers are employed [3, 9-11, 15].

The sum-differential amplitude method is considered the most effective, as it mitigates the impact of both the amplitude and phase of the signal on the stability of the direction-finding characteristics, ensuring the highest accuracy in determining the direction of the signal source.

Figure 3 illustrates the principle of forming sum-difference channels. The receiving antennas A_1 and A_2, with directional diagrams DD-1 and DD-2 exhibiting maxima in the directions of axes Z_1 and Z_2, respectively, are symmetrically rotated by an angle of $\pm\alpha_0$ relative to the equisignal direction (ESD) (Figure 3a). The angle between the axes Z1 and Z2 of the directional diagrams for antennas DD-1 and DD-2 is equal to $2\alpha_0$.

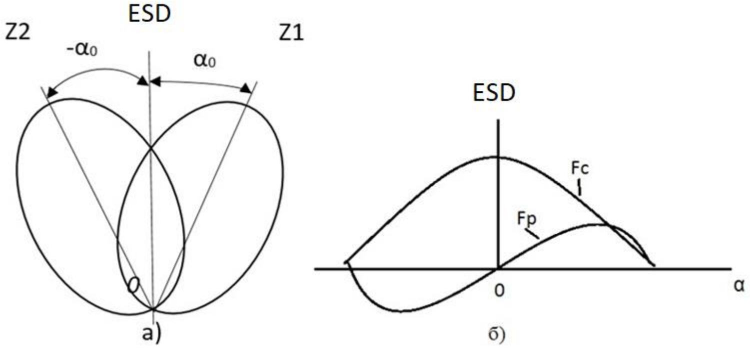

Figure 3 – The principle of formation of sum and differential DD

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Signals at the output of the antennas are determined as follows:

$$U_1(\alpha) \sim kF(\alpha_0 + \alpha)\cos\omega t,$$
$$U_2(\alpha) \sim kF(\alpha_0 - \alpha)\cos\omega t, \qquad (1)$$

where k is the proportionality factor, which includes the signal amplitude Um and the transmission coefficient of the antenna; $F(\alpha_0 - \alpha)$, $F(\alpha_0 + \alpha)$ – directivity diagrams of antennas A_1 and A_2.

The sum channel is created by summing the signals U1(α) and U2(α) from the outputs of the magnetic antennas, while the differential channel is established by calculating the difference between these same signals. This process is equivalent to generating the sum Fs(α) and differential Fd(α) directional diagrams, as illustrated in Figure 3b.

The output signals of the sum Us(α) and differential Ud(α) channels are then amplified.

$$U_s(\alpha) \sim kk_s\left[F(\alpha_0 + \alpha) + F(\alpha_0 - \alpha)\right]\cos\omega t = kk_s F_s(\alpha)\cos\omega t,$$
$$U_d(\alpha) \sim kk_d\left[F(\alpha_0 + \alpha) - F(\alpha_0 - \alpha)\right]\cos\omega t = kk_d F_d(\alpha)\cos\omega t, \qquad (2)$$

where ks and kd are channel gain coefficients.

As shown in Figure 3b, the phase of the differential signal Ud(α) changes based on the orientation of the signal source relative to the equisignal direction (ESD). This phase can either align with the phase of the sum signal or b(1)e in antiphase. The sum channel is utilized for signal detection, resulting in the output energy of the sum channel being four times greater than that of a single channel output. In contrast, the differential channel exhibits angular discriminating properties, allowing for the determination of both the magnitude and sign of the angular misalignment of the direction to the signal source from the ESD, independent of the level of the received signal [4, 8, 10, 11]. The direction-finding characteristic using the sum-difference method is described by the following relationship:

$$U_{out}(\alpha) = \frac{U_d(\alpha)}{U_s(\alpha)} \sim \frac{k_d F_d(\alpha)}{k_s F_s(\alpha)}, \qquad (3)$$

There are four methods to derive the dependence of Uout(α), which is proportional to the ratio of the signals Ud(α) and Us(α). The first method involves the direct implementation of the mathematical operation of signal division using specialized microcircuits. For this approach to be effective, the phase shifts of the channels must be identical. The second method utilizes automatic gain control (AGC) on both the sum and differential channels.

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A phase detector is employed to ascertain the magnitude and sign of the angular misalignment, using the sum channel signal as the reference voltage. Considering the operation of the AGC system, the output of the phase detector will be:

$$U_{PD}(\alpha) \sim k_{PD} \frac{k_d}{k_s} \mu\alpha \cdot \cos(\varphi_s - \varphi_d), \qquad (4)$$

where k_{PD} is the transmission coefficient of the phase detector, μ is the steepness of the working section of the differential directivity diagram in the bearing area, φc and φp are the phase shifts in the channels.

The third method involves using a phase detector to divide the output signal of the phase detector by the square of the sum channel signal following amplitude detection. The fourth method entails forming the sum and differential signals after amplifying and performing amplitude detection on the signals received from the antennas. This is followed by normalizing the differential signal with respect to the sum signal, as illustrated in Figure 4.

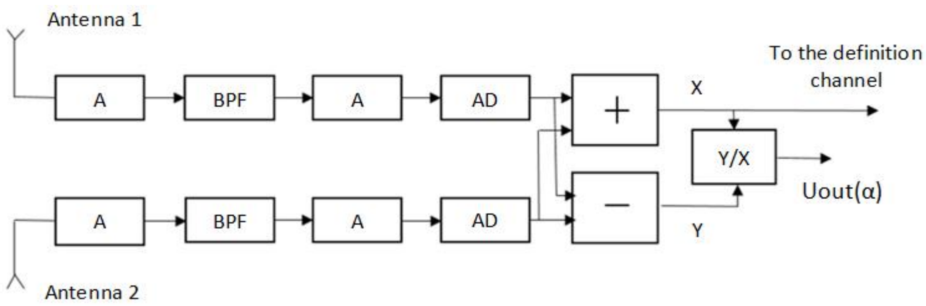

Figure 4 – Formation of bearing on the video frequency: A – amplifier; BPF – band-pass filter; AD – amplitude detector; Y/X is a divisor.

At the output of the amplitude detectors, the signals are described by the equations:

$$U_1(\alpha) = k_1 U_m F(\alpha_0)(1 + \mu\alpha),$$
$$U_2(\alpha) = k_2 U_m F(\alpha_0)(1 - \mu\alpha). \qquad (5)$$

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At identical receiving channels ($k_1 = k_2 = k$), the output of the sum and differential channels will have the following signals:

$$\begin{aligned} U_s(\alpha) &= U_1(\alpha) + U_2(\alpha) = 2kU_m F(\alpha_0), \\ U_d(\alpha) &= U_1(\alpha) - U_2(\alpha) = 2kU_m F(\alpha_0)\mu\alpha . \end{aligned} \tag{6}$$

At the output of the division circuit, a signal is obtained:

$$U_{out}(\alpha) = \frac{U_d(\alpha)}{U_s(\alpha)} = \frac{2kU_m F(\alpha_0)\mu\alpha}{2kU_m F(\alpha_0)} = \mu\alpha . \tag{7}$$

Thus, the output provides a signal proportional to the angle α, which remains independent of the signal level and phase shifts within the channels. This signal will be referred to as the direction finding characteristic.

We will simulate the sum-difference method for determining the location of an intra-pipe technical device. The transmitting and receiving antennas are multi-layer coils, which can be effectively regarded as frame antennas [11, 14, 16].

Theoretically, the directional diagram of a frame antenna is represented as a three-dimensional figure (Figure 5a). In two-dimensional sections, this diagram appears as:

- A circle in a plane that is perpendicular to the Z-axis of the spool and intersects the midpoint of the spool (Figure 5b).
- A figure resembling an "eight" in the plane of the Z-axis of the spool (Figure 5c).

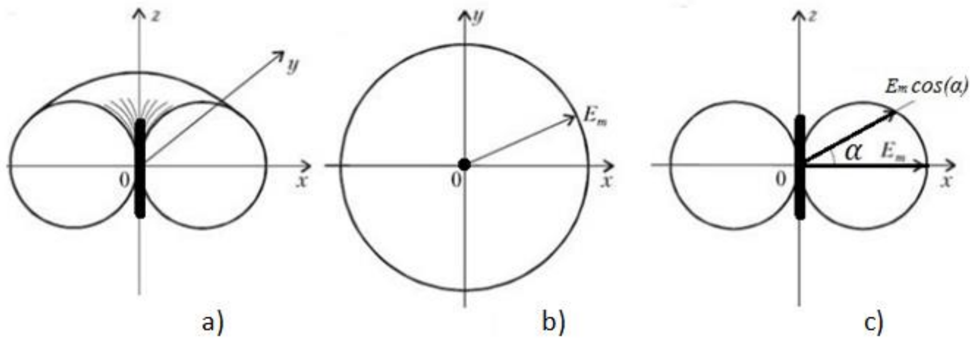

Figure 5 – Directional diagram of a loop antenna
The theoretical directional diagrams of the antennas were utilized in the simulation.

In practical applications, the primary interest lies not so much in the angular direction to the intra-pipe technological device (ITD) but rather in the distance Tx

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from a reference point on the pipeline's Tx, specifically from the perpendicular drawn from the center of the antenna axis (in the direction of the equisignal direction, ESD) to the pipeline axis. Consequently, during the modeling process, the angular direction α was converted into the distance Tx.

In this context, the direction-finding characteristic represents the relationship between the output signal and the distance Tx to the ITD along the T-axis of the pipeline from the reference point. Channel transmission coefficients were not considered in the simulation, focusing solely on the directional properties of the antennas.

Given that the directional diagrams are circular in polar coordinates and exhibit relatively wide directional properties (see Figure 5c), with identical phase diagrams, it is possible to achieve the ESD and varying values of the directional diagrams (DD) for the angle of deviation α from the ESD. This can be accomplished not only by spreading the antennas at an angle of $\pm\alpha_0$ but also by arranging them coaxially along the same axis, separated by a distance L. Both configurations for antenna placement were evaluated in the simulation.

Option 1: The modeling scheme for the sum-difference method of direction finding, featuring coaxially located antennas (α_0=0), positioned along one axis at a distance L apart, is illustrated in Figure 6.

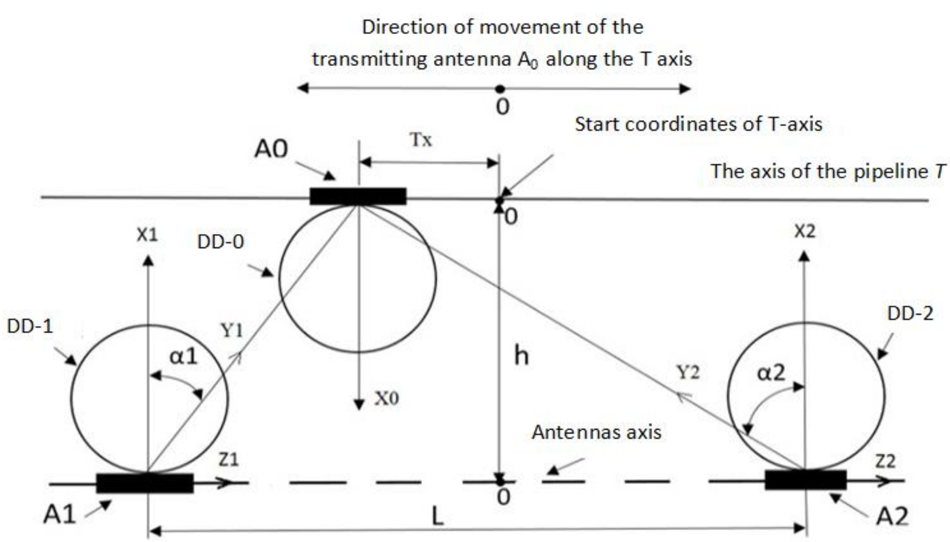

Figure 6 – Simulation scheme of the sum-difference method of direction finding with coaxial arrangement of antennas (α_0 = 0).

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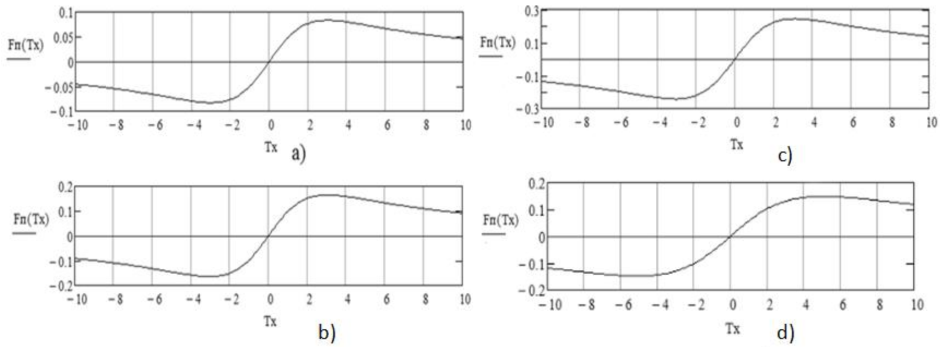

Figure 7 – Bearing characteristic as a function of Tx:
a) L = 0.5 m, h = 3 m; b) L=1.0 m, h = 3 m; c) L = 1.5 m, h = 3 m; d) L = 1.5 m, h = 5 m.

Option 2: The simulation scheme for the sum-difference method of direction finding involves two antennas positioned on the same axis at a distance L apart, with an angular shift of their directional diagrams by $\pm\alpha_0$. This configuration is illustrated in Figure 8. The results of the simulation for $\alpha_0 = \pi/6$ are presented in Figure 9.

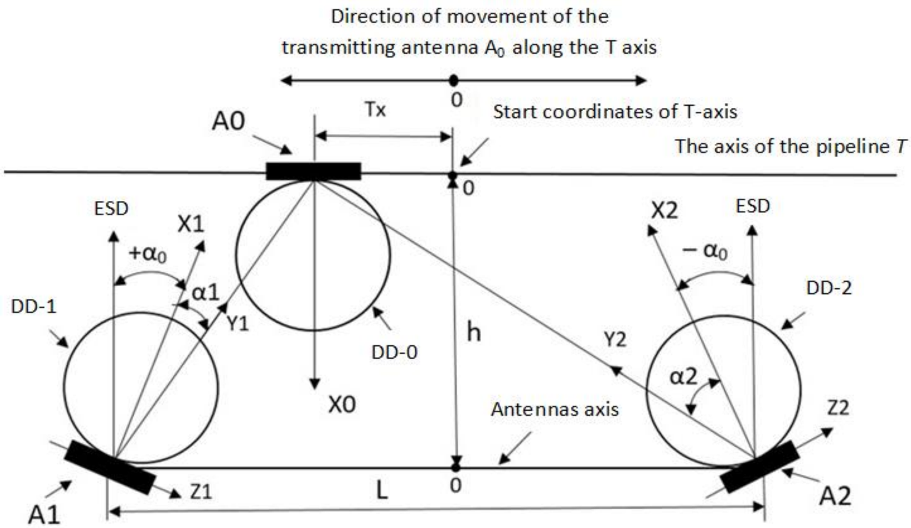

Figure 8 – Simulation scheme of the sum-difference method of direction finding with opposite angular displacement of the DD by an angle of $\pm\alpha_0$

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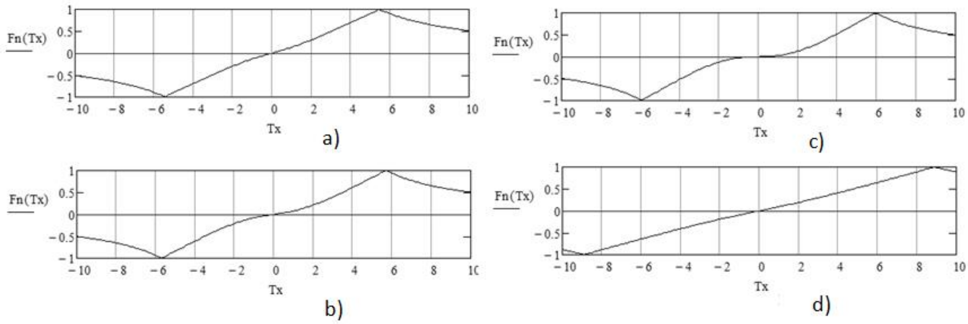

Figure 9 – Bearing characteristic as a function of Tx:
a) L = 0.5 m, h = 3 m; b) L=1.0 m, h =3 m; c) L = 1.5 m, h = 3 m; d) L = 0.5 m, h = 5 m.

<u>For the coaxial antenna configuration:</u>

- The largest output signal from the differential channel, and consequently after normalization, is achieved at a distance L=1.5 m.
- The length of the linear section of the direction-finding characteristic remains relatively unaffected by the antenna spacing L and is approximately ±2 m.
- As the distance of the antennas from the pipeline increases (with an increase in h), the steepness of the direction-finding characteristic decreases.
- A notable advantage is the independence of the direction-finding characteristic from the angle of rotation of the antenna system around its axis, as the antenna appears as a circle in the plane perpendicular to the axis (see Figure 5b).

<u>And for the configuration with antennas spaced at an angle of $\pm\alpha_0$:</u>

- Simulation results indicate that the optimal angle is $\alpha_0=\pi/6$. Other angle values result in a reduction of the linear (working) section of the bearing characteristic.
- The largest output signal from the differential channel, along with a wider linear section of the bearing characteristic, is obtained at L=0.5 m.
- As the distance of the antennas from the pipeline increases (with an increase in h), the linear section of the direction-finding characteristic expands, and its steepness decreases. In practice, it is possible to implement a corrector for the steepness of the direction-finding characteristic based on the distance h to the pipeline.
- The output signal from the diversity channel in the configuration with angularly spaced antennas is greater than in the case of coaxial arrangement.

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- The span of the bearing characteristic remains constant at ±1, in contrast to the coaxial antenna option, which corresponds to a higher signal level at the output of the dividing device.
- A disadvantage of this configuration is its dependence on the steepness of the direction-finding characteristic with respect to the angle of rotation of the antenna system around its axis. When measuring a relatively concealed (underground) oil pipeline, this aspect significantly limits the practical application of this antenna positioning variant.

Therefore, in practical scenarios, it is essential to orient the antennas so that they and the intended axis of the pipeline lie within the same plane. This orientation ensures that the direction-finding characteristic maintains sufficient steepness, regardless of the angle of rotation of the antenna system around its axis.

Further experiments revealed that the optimal distance between the antennas (magnetic receivers) in the coaxial positioning configuration is approximately L=1.5 m, with the antenna system positioned as close as possible to the pipeline axis.

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III. Conclusion

In this study, we explored the development and performance of a search system for intra-pipe technological devices (ITDs) in oil pipeline transport. Our findings highlight the efficacy of the sum-difference method for accurately determining the location of ITDs, emphasizing the importance of both coaxial and angularly spaced antenna configurations.

The coaxial arrangement demonstrated optimal signal output at a distance of 1.5 m, with a consistent direction-finding characteristic that remains independent of the antenna's rotational angle. Conversely, the angularly spaced configuration offered higher signal levels but displayed a dependence on the angle of rotation, which poses challenges for practical applications, particularly in underground pipeline monitoring.

Through simulations, we established that the optimal angular shift for the antennas is $\pm\pi/6$, and we identified that the distance between antennas significantly influences the performance of the direction-finding characteristics. These insights contribute valuable knowledge for enhancing the effectiveness of monitoring systems in oil pipeline transport, ultimately supporting safer and more efficient operations.

Future work should focus on refining these systems further and exploring advanced technologies that could mitigate the limitations identified, particularly in relation to antenna positioning and signal processing.

IV. Acknowledgements

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