UDC 621.398
DOI: 10.15587/1729-4061.2020.212345

DETERMINING A TECHNIQUE FOR TRANSMITTING MEASURING DATA ON THE SPATIAL POSITIONING OF THE PIERCING HEAD IN SMALL-SIZE INSTALLATIONS DURING CONTROLLED SOIL PIERCING

V. Sakhatsky
Doctor of Technical Sciences, Professor*
N. Lyubymova
Doctor of Technical Sciences, Professor
Department of Agrotechnology and Ecology***
E-mail: nina.lioubimova@gmail.com
V. Vlasovets
Doctor of Technical Sciences, Professor
Department of Tractors and Cars***
V. Suponyev
PhD, Associate Professor
Department of Build and Travelling Machines**
O. Koval
PhD, Associate Professor*
A. Naumenko
PhD, Associate Professor
Department of Construction and Civil Engineering***
T. Vlasenko
PhD
Department of Production Organization, Business and Management***
E-mail: tvlasenko15@gmail.com
Y. Chepusenko
Postgraduate Student*
*Department of Metrology and Life Safety**
**Kharkiv National Automobile and Highway University
Yaroslava Mudroho str., 25, Kharkiv, Ukraine, 61002
***Kharkiv Petro Vasylenko
National Technical University of Agriculture
Alchevskykh str., 44, Kharkiv, Ukraine, 61002

For laying of underground utility systems in urban conditions by the method of horizontally directed soil piercing, small-sized units are designed. Such units should have measurement systems for determining the spatial position of the piercing head. In known systems, the surface layer of the soil is used as a data transmission line for transmitting measurement information.

This method of transmitting information signals in urban conditions is not very acceptable. Ground-based objects reflect electromagnetic radiation of the head transmitter which leads to distortion of the directional diagram of the emitter and complicates the reliable reception of measurement information.

It was proposed to use an autonomous measuring system with an operating frequency of 5 GHz based on Wi-Fi technologies and an unconventional method of transmitting measurement information using hollow steel bars in the piercing unit itself. This transmission line has periodic discontinuities because of the bar design. These discontinuities accumulate as the piercing head advances. For the basic vibration type H11, more accurate analytical expressions were obtained for calculating the power transfer coefficient of the measurement signal in such non-uniform lines. It was shown that inhomogeneity of the transmission line in comparison with its surface resistance does not significantly affect the transmission coefficient.

For example, damping in the line increased by 1.2 dB with the maximum length of inhomogeneity of 5 mm and the total length of jointed bars of 50 m. It has been theoretically proven that the range of soil piercing with reliable signal reception can be up to 50 meters.

The proposed method for transmitting information signals makes it possible to reduce the transmitter power, ensure noise immunity of the measuring system, and reliable reception of the measuring information throughout the entire piercing path

Keywords: piercing head, measuring system, waveguide path, inhomogeneity, ABCD matrix, transmission coefficient

Received date 28.07.2020
Accepted date 15.09.2020
Published date 31.10.2020

1. Introduction

Special digging machines are used currently in many countries when laying underground utility systems of various types. They are designed to form holes with a complex path. Vermeer, Straight Line, Ditch Witch (USA), Tracto Technik (Germany) are the world's leading manufacturers of such machines [1]. However, initial hole entry for these machines is provided from the surface. This requires a large operation space which makes them difficult to operate in a constrained urban environment.

Small-size units developed recently for piercing track holes at depths of up to 3 m can be their alternative.

They are using the principle of hole formation by means of radial soil compaction with a piercing head and operate from a small pit sufficient for the unit and its operator.

The inaccuracy of placement of the piercing units relative to the track axis, soil non-uniformity, bending of extension rods during the advance of the piercing head cause a significant deviation of the pierced track from the set path. Significant additional economic and technological costs arise as well. Therefore, the piercing units must be equipped with systems for controlling the path of the piercing head. The measuring system that enables spatial positioning of the piercing head is the main component of such a unit.

Lack of measurement systems for spatial positioning of the piercing head which would be adequate to the cost of small-sized units and meet their technological purpose is the main obstacle for the widespread use of small-sized piercing units.

The principle of operation of the measuring systems used currently is based on the transmission and reception of the measuring signal as electromagnetic radiation. The surface soil layer serves as a line for transmission of the measurement signal.

The transmitting device is placed in the piercing head and its emitters create a certain directional diagram in the surrounding space. When the direction of movement of the piercing head changes, the directional diagram changes predictably. In most cases, the receiving device located on the ground surface above the emitters detects this change and enables spatial spotting of the piercing head according to the level of received radiation.

The urban environment abounds in industrial electromagnetic interference reducing the signal-to-noise ratio required for the measurement systems when this method of transmitting the measuring data is used.

Various urban structures, reinforced concrete, and metal structures near or in the path of the piercing track reflect electromagnetic radiation and considerably distort the directional diagram of the emitter. Because of this phenomenon, the actual position of the piercing head in soil cannot be determined. If measurement conditions are such that urban objects exclude placement of the receiver above emitters, then the continuous reception of the measuring signal is broken.

All these factors indicate that the existing method of transmitting the information signal to the receiver through the soil layer makes it difficult to receive measurement data in urban conditions reliably and continuously when using known measuring systems. As a result, controlled soil piercing becomes impossible.

It can be added to the above that the use of known measuring systems in small-sized units does not correspond to their adequate cost in many respects.

Therefore, search for other methods of continuous transmission of measurement information and the creation of corresponding measuring systems for controlled soil piercing by small-sized units are relevant.

2. Literature review and problem statement

The need to measure parameters of underground utility routs has acquired particular relevance when piercing oil, gas, geothermal and other holes. A directional survey is the main measurement method in this case.

An inclinometer consists of downhole and surface instruments. To measure the azimuth and zenith angle of the hole, it contains sensors located in the hole instrument and responding to changes in the magnetic and gravitational fields of the earth. The downhole instrument is powered from the surface instrument via a cartometry cable. Information on the angular position of the hole is transmitted via the same cable [3]. Various types of inclinometers are used in the inclinometry of holes. The main solutions in this field are aimed at improving the sensitivity of sensors and the accuracy of measurement [4, 5].

Because of the bulkiness of the equipment used, such methods of underground routing are inapplicable practically in routing urban utility systems and measuring their parameters.

The method of horizontally directed soil piercing is currently widely applied for these purposes. The application of this method of trenchless laying of undersoil utility lines has entailed the creation and improvement of horizontal soil piercing units. Such piercing is done using a pneumatic punch or a piercing head. Methods and regularities of the soil piercing processes, mechanisms used in routing the utility systems are described in [6, 7] from which it follows that the work quality is determined by the accuracy of the hole path. The need for effective control of the direction of the tool movement in soil during holing was also confirmed in [8]. It is known that machines for horizontally directed soil drilling operate from the surface. They have large dimensions and therefore are unsuitable for operation in confined urban conditions [7, 8]. Therefore, small-sized piercing units are being developed as they are more acceptable for urban conditions [9, 10]. Pneumatic punches or piercing heads are working (piercing) bodies of mechanical units designed to lay leader holes for relatively short distances. They require correction of movement in soil to a greater extent [11]. However, the study did not offer special control systems for such small-sized units and their working tools with taking into account specifics of their operation.

Thus, continuous control of the piercing head advance and timely correction of its track is an important task of the piercing process which was confirmed in [12].

The hole track can be effectively corrected by means of a special piercing head design. For that, the shape of its tip must promptly change and the head should turn at a set angle in its advancement [8].

To prevent the piercing head deviation from the specified track, it is necessary to have information-measuring systems for determining the spatial position of the head in order to control its further movement [13]. For that, the measuring systems must determine the angle of deviation from the axis of the track and the angle of turning of the piercing head in the first place.

Electromagnetic methods (ferroprobe, induction, radar and radio scanning) are most widely used in determining underground coordinates of moving metal objects [14].

As a rule, imported equipment is used in this case, in particular, the MAGstir navigation system (Impact Drilling LTD, England), Mark 111, 1V, V, Eclipse positioning systems (Digitrack Co., Germany), and others [15, 16]. The principle of operation of such devices implies using a pneumatic punch as a source of electromagnetic field by including in its design devices emitting magnetic field or electromagnetic radiation. The receiver is located on the ground surface above the pneumatic punch and determines its coordinates by the electromagnetic field it is emitting.

The MAGstir system includes a source of the constant magnetic field which ensures detection of its weak damping in soil and makes it possible to determine the punch coordinates at great depths. However, the presence of metal objects in the ground and on its surface distorts the directional diagram of the source. In urban conditions, in the vicinity of many reinforced concrete buildings and structures, the reliability of determining coordinates of the punch decreases.

The Mark System uses a low-frequency electromagnetic field to reduce the effect of small metal objects on the radiation pattern of the emitter. Considering that urban reinforced concrete structures are bulky, it is difficult to use such systems in a city as well.

Main development studies to improve low-frequency measuring systems are aimed at the improvement of their measurement accuracy and simplification of the measuring system design. For this purpose, it was proposed in [17] to use a radiation source in a form of two identical coaxial inductors creating a low-frequency alternating magnetic field. The coils are antiphase excited and form a total-difference directional diagram in the environment. Two receiving antennas are positioned so that the difference signal is zero. Using a special measurement technique, pitch and direction of the punch movement are determined by the spatial position of the receiving antennas. In urban conditions, where walls of buildings largely distort the emitter radiation pattern, the use of such a measuring system does not allow to determine the punch coordinates reliably.

Currently, measuring systems in a higher frequency range are developed which makes it possible to more accurately determine coordinates and direction of movement of the pneumatic punch or piercing head and increase the noise immunity of the measuring system.

In this case, two spaced receiving antennas are used. The location and direction of the punch advance can be judged by the level or time lag of the signals induced in these antennas by the punch emitters.

For example, a method was proposed in [18] for determining the angle of deviation of a pneumatic punch from the set path. The punch is an unbalanced vibrator operating at 150 MHz. The vibrator's radiation is received by two antennas installed in front of the emitter symmetrically to the axis of the movement path. The vibrator is powered from a generator via a radio-frequency cable laid along the hole formed by the pneumatic punch.

This method makes it possible to increase the noise immunity of the measuring system, more accurately measure the angle of deviation of the track from the set direction, however, only in a horizontal plane. Receivers should be located in a pit that may require additional destruction of the traffic-bearing surface when the route is sufficiently long.

The known low-frequency and high-frequency measuring systems feature the use of the same line of measurement signal transmission. The ground surface layer serves as such a line.

In this case, emitters of the information signal transmitter located mostly inside the piercing tool create an electromagnetic (magnetic) field in an environment with a definite and predictable directional diagram. The radiation pattern is generally wide and also changes predictably in shape and direction as the piercing tool moves. The receiver records the change in radiation pattern using one or two spaced-apart antennas. The spatial position of the piercing tool is determined by the level of the received signal or its delay time.

The use of such measuring systems is often difficult when working in conjunction with modern small-sized piercing units in confined urban conditions. This is because of the fact that the urban environment, in addition to a high level of industrial noise which reduces the signal-to-noise ratio is characterized by the presence of a large number of reinforced concrete buildings and various reinforced concrete and metal structures. These structures can be located in the direction of the route being laid or next to it. The reflectivity of such structures is high for both low-frequency and high-frequency ranges. In this case, the directional pattern of the emitter changes unpredictably and it is impossible to establish the real position of the piercing tool. The presence of building structures, fountains, greenery in the direction of the route generally hinders placement of the receiving device above the emitter.

As a result, the continuous reception of the signal-bearing information on the current path of the piercing tool is disrupted. Because of this phenomenon, the soil may be pierced in an unknown direction, that is, controlled soil piercing becomes impossible.

The existing methods and systems for measuring coordinates of the piercing tool have a complex design and require additional calculations to determine the position of the piercing tool. They are very expensive (imported systems are estimated at tens of thousands of dollars) and require a fairly high transmitter power because of weakly directed radiation. Their cost is inadequate for the cost of small-sized piercing devices.

The use of the space surrounding the transmitter as an open transmission line to obtain continuous and reliable information is difficult in urban environments.

Thus, the problem of establishing other methods of transmitting information and corresponding inexpensive measuring systems to ensure continuously controlled piercing of soil with small-sized units in urban conditions is actual.

3. The aim and objectives of the study

The study objective is to establish a method for creating a closed transmission line and corresponding transceiver devices that could be used in a measuring system to perform continuous controlled piercing of soil with modern small-sized units.

To achieve the objective, the following tasks were set:

– to determine the principle of construction of the measuring system and structure and circuitry of the transceiver devices;

– to estimate the length of the route to be laid when using metal bars of the piercing mechanism as a closed and directional transmission line for the measuring signal.

4. The principle of construction, structure, and circuitry of the measuring system

For today, Wi-Fi technologies are widely used to exchange information between its source and a receiver, mainly in on-ground conditions. These are fairly simple and inexpensive devices with a well-developed technology of their manufacture using low-power supplies [19]. The possibility of their use in measuring systems was discussed in [20] for various purposes.

The principles of using the Wi-Fi technology to create measuring systems for determining azimuth, zenith angle, and the angle of turning the piercing head relative to its axis are considered in [21].

In the measuring system proposed here, information was transmitted with a 2.4 GHz carrier frequency using two modules of the ESP8266 series. These modules were located inside the piercing head and in the receiving device on the soil surface. An MPU-6050 type sensor that contains an accelerometer and a gyroscope was connected to the transmitting module.

The surface layer of the soil was used as a communication line between the transmitting and receiving devices. Experimental studies have shown that it is possible to determine the spatial position of the piercing head at small (about 1 m) depths in dry soils. At greater depths and in the presence of asphalt coating, a strong signal damping is observed.

Thus, the use of Wi-Fi technologies when creating energy-saving measuring systems in the microwave range is possible. However, it has its limitations for open transmission lines. Therefore, it is of interest to search for other ways of transmitting an information signal for such measuring systems.

Bars in a form of ≈50 cm long steel tubes with inner and outer diameters of 3.95 cm and 6.35 cm, respectively, are used in small-sized soil piercing units to advance the piercing head. Such a bar is essentially a round metal waveguide through which the basic oscillations of H_{11} type can propagate at a frequency of 5 GHz and the bar itself can serve as a measurement signal transmission line. Since the 5 GHz frequency is one of the working frequencies of Wi-Fi systems, the measuring system for determining the spatial position of the piercing head can be represented as in the following diagram (Fig. 1).

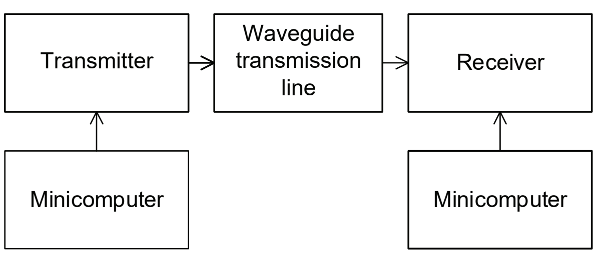

Fig. 1. Block diagram of waveguide transmission of data on the spatial position of the piercing head

The information-measuring system consists of a transmitter and a receiver. A Raspberry Pi 3 minicomputer of model B+ (Great Britain) [22] with a BMX055 spatial position sensor (Germany) connected to it [23] can act as a transmitter.

The Cypress CYW43455 module built into Raspberry Wi-Fi features a 2.4 GHz and 5GHz dual-band transceiver supporting 20 MHz, 40 MHz, and 80 MHz channel widths and a maximum throughput of up to 433 Mbps. This minicomputer can operate self-sufficiently using a 5 V 2.5 A battery. It has dimensions of 85.6×53.98×17 mm which makes it possible to develop low-cost small-sized portable measuring systems based on it. They can be placed inside the piercing heads commonly used in practice. The board has 40 GPIO connectors, supports I2C and SPI interfaces for connecting various sensors.

The operating frequency range of the transceiver in a 5 GHz mode is within 4900-5845 MHz. Depending on the selected channel, modulation type and standard (IEEE 802.11a, IEEE 802.11n or IEEE 802.11ac), the receiver sensitivity ranges from 94.5 dBm to 65.5 dBm (for more detail, sensitivity for each type see in technical documentation for the Cypress CYW43455 module, Table 36 [24].

The receiver is implemented as a Raspberry Pi 3, model B+ minicomputer with a display connected to it for the information output.

The principle of measuring the spatial position of the piercing head will be as that indicated in [21] taking into account specifics of the Wi-Fi modules used for the 5 GHz frequency.

The measuring system with a waveguide transmission line has a clear economic advantage over inclinometric and radio-wave systems described in [14]. It is distinguished by its simplicity, absence of additional costs for the purchase and creation of special lines for powering and transmission of measurement signals.

The proposed structure of the measuring system design, including the transmission line, is built on a modular principle which makes it more flexible with the possibility of replacing its modules with more modern ones that are under development.

In this case, the measurement signal will be received continuously and regardless of the presence or absence of building barriers on the ground surface. Its level will not depend on the depth of the track and electrophysical characteristics of soil. The degree of damping of the measurement signal will depend only on electrophysical characteristics of the bars and length of the route being laid.

In practice, to transmit power and information signals, round copper waveguides are used for the waves of H_{01} type. This type of oscillation has minimal losses in wave propagation but belongs to the highest types of oscillation. Therefore, to maintain it, waveguides of a special design are made. Such designs are unacceptable for piercing bars. Therefore, it is necessary to study the possibility of using metal bars when oscillations of the main type and of H_{11} type with higher damping are propagating along them as a carrier wave.

5. Estimation of length of the route being laid

Let us estimate the length of the route that can be laid using a measuring system built on the basis of Wi-Fi technologies.

The piercing head is horizontally advanced using metal bars which are sequentially connected to each other as the head moves.

The bars are made from standard tubes of a certain length with their ends having external and internal threads for connecting them to each other. The length of internal and external threads can vary in the process of threading. Therefore, a threaded section of the waveguide appears in the joints of the bar sections. The tube wall in these places has not smooth cylindrical but helical surface. As a result, an inhomogeneity appears at the junction of the two bars which introduces additional damping of the wave as it propagates. Therefore, these inhomogeneities must be taken into account when assessing the possibility of using tubular bars as a waveguide transmission line.

Let us represent a helical line segment as an equivalent circular waveguide of length Δl with some equivalent internal diameter depending on the thread depth. This section of the waveguide will be considered as a periodic local inhomogeneity of the transmission line along its length. In this case, the measuring channel will be a transmitting device (information signal generator) and a receiving device interconnected by a non-uniform transmission line (Fig. 2).

The transmission line of the measuring channel can be represented as a cascade connection of n separate sections of length L_s. Each section consists of uniform sections of the waveguide line (bars) of length l and an inhomogeneity (threaded connection) of length Δl occurring at the junction of two waveguides. The cascade connection of the section ends with a circular waveguide segment of length l which is a part of the matching device and brings about damping of oscillations of higher types that occur at the last threaded connection of the entire transmission line. The matching device provides matching of polarizations of emitted and received waves as well as matching of the output resistance of the transmission line and the input resistance of the receiving device.

When calculating complex microwave routs, they are often represented as segments of equivalent two-wire lines [25]. Such lines have one input and one output, therefore they are represented as quadrupoles. A transmission line containing local discontinuities can be represented as a cascade connection of quadrupoles.

The matrix method is one of the methods for analyzing complex circuits. For this purpose, S scattering matrices, wave T transmitting matrices, and classical $ABCD$ transmission matrices are used [26]. The wave and $ABCD$ matrices make it possible to convert a cascade connection of quadrupoles to one equivalent quadrupole. With wave characteristics of each segment of the waveguide line (bar) being known, it is possible to obtain output characteristics of the signal transmitted through the piecewise non-uniform transmission line.

The unnormalized transmission matrix of a segment of a circular waveguide of length l and characteristic impedance Z_w takes the form [27]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \mathrm{ch}(\gamma l) & Z_w \, \mathrm{sh}(\gamma l) \\ \mathrm{sh}(\gamma l)/Z_w & \mathrm{ch}(\gamma l) \end{bmatrix}, \tag{1}$$

where $\gamma=\alpha+j\beta$ is the complex constant of propagation; α is the damping coefficient; β is the phase constant.

The investigated soil piercing unit measurement data is a cascade connection of segments of a circular waveguide connected by means of a threaded connection (Fig. 3).

In general, such a modular waveguide can be represented as a series connection of n segments of a uniform and non-uniform transmission line (Fig. 3). A uniform transmission line is a section of a circular waveguide (bar) of length l and a characteristic impedance Z_w. A non-uniform transmission line is a gap Δl in the joint of bars with characteristic impedance $Z_{w\,jt}$. In absence of losses, the scattering matrix of such a segment will take the form [27]:

$$S = \begin{bmatrix} r & t \\ t & r \end{bmatrix}. \tag{2}$$

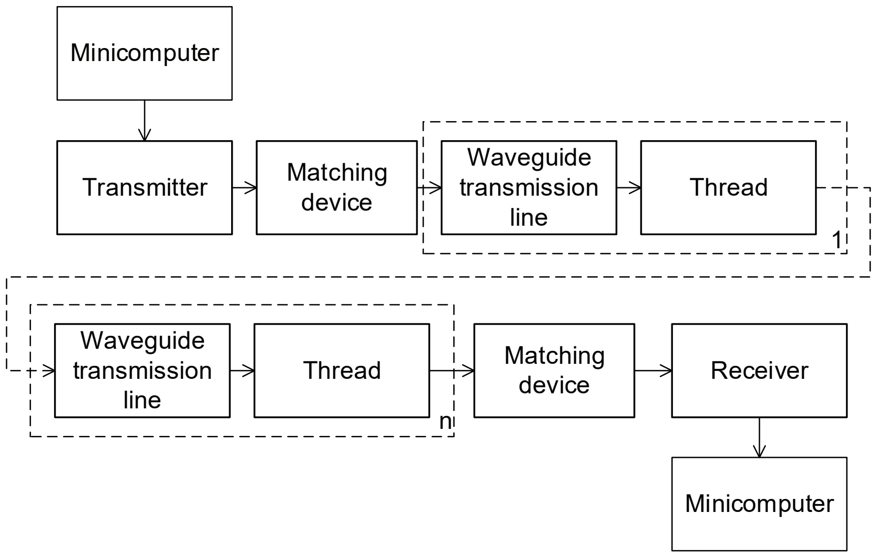

Fig. 2. Measuring channel of determining the spatial position of the piercing head

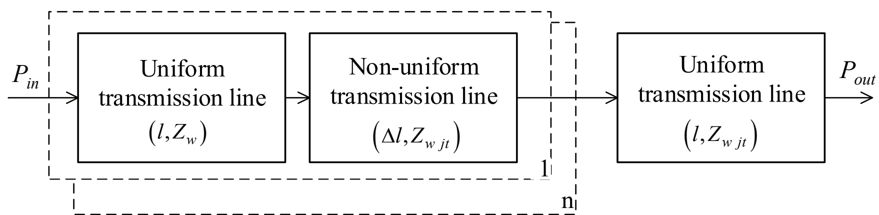

Fig. 3. Waveguide soil piercing unit measurement data

Elements of the matrix S are defined as in [27]:

$$r = \frac{j\left(Z_{ot}^2 - 1\right) tg\left(\beta_{jt}\Delta l\right)}{2Z_{ot} + j\left(Z_{ot}^2 + 1\right) tg\left(\beta_{jt}\Delta l\right)}, \tag{3}$$

$$t = \sqrt{1 - |r|^2} \cdot e^{-j\beta_{jt}\Delta l}, \tag{4}$$

where $Z_{ot} = \dfrac{Z_{w\,jt}}{Z_w}$; β_{jt} is the phase constant in the transmission line segment Δl.

Let us transform the scattering matrix S into a non-normalized $ABCD$ matrix. Using the well-known transformation equations for the line segment [28], elements of the unnormalized transmission matrix (1) of the circular waveguide segment can be determined. As a result, the following is obtained:

$$A_{jt} = \frac{1 - r^2 + t^2}{2t}, \tag{5}$$

$$B_{jt} = \frac{1 + 2r + r - t^2}{2t} \cdot Z_w, \tag{6}$$

$$C_{jt} = \frac{1 - 2r + r^2 - t^2}{2t \cdot Z_w}, \tag{7}$$

$$D_{jt}=\frac{1-r^2+t^2}{2t}. \tag{8}$$

Let us turn to the diagram of the soil piercing unit measuring signals from the transmitter in the piercing head to the receiving device (Fig. 2). The diagram shows that the transmission line contains *n* identical sections. Each section contains a transmission line in a form of a circular waveguide of length *l* with its own characteristic impedance and a non-uniformity as a waveguide segment of length Δl with a characteristic impedance of the joint. Then the resulting *ABCD* matrix for one section can be defined as the product of matrices of waveguides of length *l* and Δl:

$$\begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix}=\begin{bmatrix} \mathrm{ch}(\gamma l) & Z_w \mathrm{sh}(\gamma l) \\ \mathrm{sh}(\gamma l)/Z_w & \mathrm{ch}(\gamma l) \end{bmatrix}\cdot\begin{bmatrix} A_{jt} & B_{jt} \\ C_{jt} & D_{jt} \end{bmatrix}. \tag{9}$$

The total unnormalized transmission matrix for a waveguide transmission line consisting of *n* sections connected in series will be determined as the product of *n ABCD* matrices for each section:

$$\begin{bmatrix} A_{s\Sigma} & B_{s\Sigma} \\ C_{s\Sigma} & D_{s\Sigma} \end{bmatrix}=\begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix}\cdot\begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix}\cdot\ldots\cdot\begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix}. \tag{10}$$

The measurement data transmission line consisting of *n* cascades of waveguide sections ends with a waveguide of length *l* (Fig. 3) with the transmission matrix described by expression (1). Then the transmission matrix of the entire transmission line can be written as:

$$\begin{bmatrix} A_l & B_l \\ C_l & D_l \end{bmatrix}=\begin{bmatrix} A_{s\Sigma} & B_{s\Sigma} \\ C_{s\Sigma} & D_{s\Sigma} \end{bmatrix}\cdot\begin{bmatrix} \mathrm{ch}(\gamma l) & Z_w \mathrm{sh}(\gamma l) \\ \mathrm{sh}(\gamma l)/Z_w & \mathrm{ch}(\gamma l) \end{bmatrix}. \tag{11}$$

Let us find the damping function of the entire soil piercing unit the measuring signal which means a ratio of powers of the supply wave P_{input} at the line input to power at its output P_{output} at a matched load.

Typically, the function of signal damping in the transmission line is determined from equation [29]:

$$K_{\mathrm{dB}}=10\lg\left(\frac{1}{|S_{21}|^2}\right). \tag{12}$$

An element of the scattering matrix S_{21} can be determined from the well-known formulas of transition from the *ABCD*-matrix to the *S*-matrix [28]. Assume that the waveguide transmission line has matched impedances at the input and output which are equal to its characteristic impedance Z_w. In this case, the following is obtained:

$$S_{21}=\frac{Z_w}{A_l Z_w + B_l + C_l Z_w^2 + D_l Z_w}. \tag{13}$$

To calculate element S_{21} of the scattering matrix of the entire transmission line, it is necessary to determine the number of its parameters in accordance with expressions (1–4). These include:

– complex propagation constant γ;

– wave impedance for a waveguide section of a transmission line of length *l*;

– phase constant of propagation β_{jt};

– wave impedance $Z_{w\,jt}$ for a waveguide segment of length Δl formed by joining two metal bars.

To determine these parameters, let us turn to the actual designs of elements of the soil piercing unit. The bars of length 500±5 mm have inner radius a=19.75 mm and outer radius α_{out}=31.75 mm. The threaded gap between the bars Δl=(2…5) mm. The average radius of the waveguide gap is α_{cm}=22 mm.

At a carrier frequency of the information signal of 5 GHz (wavelength λ=6 cm), a wave of the main H_{11} type of oscillations with a propagation constant γ will propagate in a metal bar with these radii.

In this case, its phase constant β and damping coefficient α conditioned by the wave damping in the waveguide walls are determined by equations [30]:

$$\beta=\frac{2\pi}{\lambda}\cdot\sqrt{1-\left(\frac{\lambda}{3.41*a}\right)^2}, \tag{14}$$

$$\alpha=\frac{R_S}{a\sqrt{\frac{\mu_a}{\varepsilon_a}}\sqrt{1-\left(\frac{\lambda}{3.41*a}\right)^2}}\cdot\left[0.42+\left(\frac{\lambda}{3.41*a}\right)^2\right], \tag{15}$$

where $R_S=\sqrt{\frac{f\pi\mu}{\delta}}$ is the surface resistance of the material from which the waveguide is made; *f* is the frequency of bearing oscillations; μ is the absolute magnetic permeability of the material; δ is the specific electrical conductivity of the material; μ_a is the absolute magnetic permeability of the medium filling the waveguide; ε_a is the absolute dielectric permeability of the medium filling the waveguide.

Let us consider a waveguide formed by a threaded joint between two bars. It has an equivalent radius a_{cm} and, due to its small length Δl, there is no loss in it. That is, the damping coefficient of a given waveguide is α_{jt}=0. Then the constant of propagation of an electromagnetic wave in the waveguide $\gamma_{jt}=\beta_{jt}$ and can be determined from the formula:

$$\beta_{jt}=\frac{2\pi}{\lambda}\sqrt{1-\left(\frac{\lambda}{3.41\cdot a_{jt}}\right)^2}. \tag{16}$$

Using the equation given in [25], the equation for the characteristic impedance of a circular waveguide when a wave of H_{11} type propagates in it, the characteristic impedance of the bar is obtained:

$$Z_w\approx 0.94\sqrt{\frac{\mu_a}{\varepsilon_a}}\cdot\frac{2\pi}{\beta\cdot\lambda}. \tag{17}$$

The characteristic impedance of the segment Δl at the joint of two bars

$$Z_{w\,jt}\approx 0.94\sqrt{\frac{\mu_a}{\varepsilon_a}}\cdot\frac{2\pi}{\beta_{jt}\cdot\lambda}. \tag{18}$$

To determine losses of the electromagnetic signal propagating along the bars of the piercing unit, it is necessary to know the value of the surface resistance R_s. According to [31], the specific resistance of steel with a mass fraction of carbon 0.2 % ρ=10^{-7} Ohm·m and its relative magnetic permeability μ_r=120.

Taking into account these parameters of the transmission line and formulas (1) to (18), the level of the information signal damping can be calculated. The calculations were performed using the PTC Mathcad package (USA) and their results are shown in Fig. 4–8.

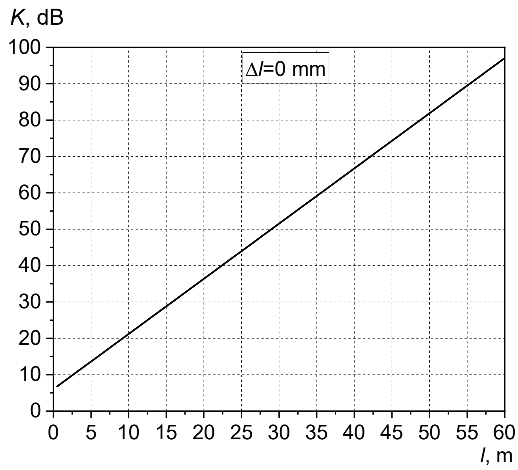

Fig. 4. Dependence of the transmission coefficient of a uniform line on the line length

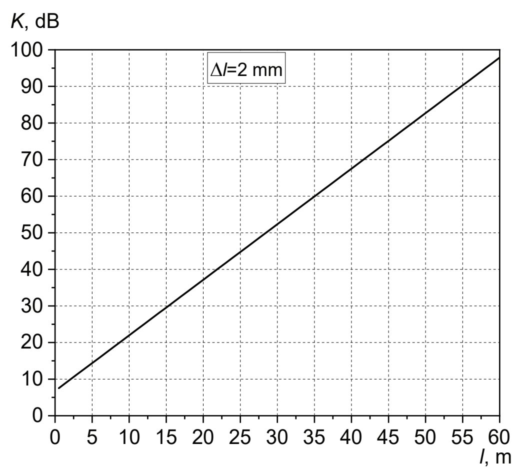

Fig. 5. Dependence of the transmission coefficient of a non-uniform line on the line length at Δ*l*=2 mm

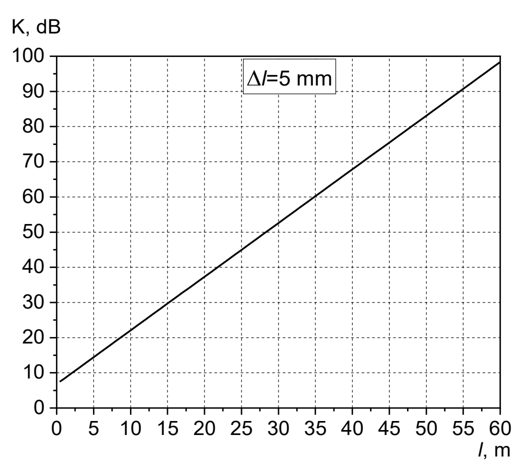

Fig. 6. Dependence of the transmission coefficient of a non-uniform line on the line length at Δ*l*=5 mm

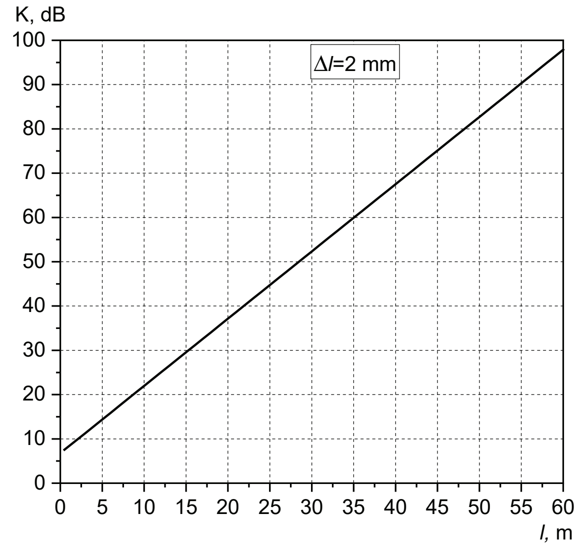

Fig. 7. Increase in the transmission coefficient of a non-uniform line in comparison with a uniform line depending on the line length

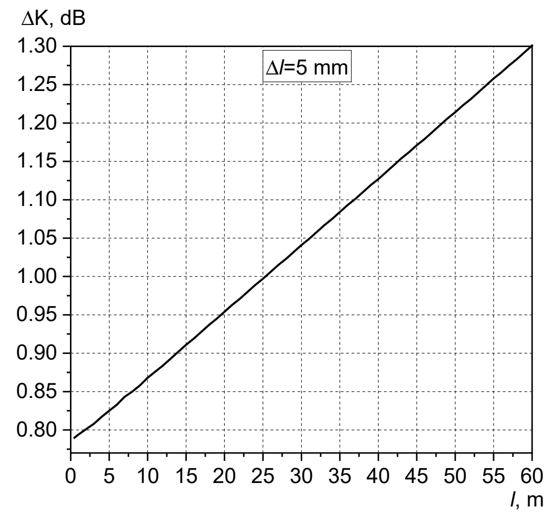

Fig. 8. Increase in the transmission coefficient of a non-uniform line in comparison with a uniform line depending on its length

Fig. 4 shows the dependence of the transmission coefficient on the length of the line which does not have heterogeneous inclusions (Δ*l*=0 mm).

Fig. 5, 6 show the dependence of the transmission coefficient of a non-uniform line on the line length at different gaps in the joints between bars.

An increase in the transmission coefficient of a non-uniform line with a joint length of 2 mm and 5 mm in comparison with a uniform line is shown, respectively, in Fig. 7, 8.

6. Discussion of the results obtained in studying the method of information signal transmission and the principle of the measuring system construction

The study results have confirmed the possibility of creating control and measuring systems according to the block diagram shown in Fig. 1 for controlled soil piercing with small-sized units. Selected circuitry for the transceiver devices of the measuring system in the 5 GHz range is easily placed in a small-sized piercing head. It is characterized by low power consumption and cost and has sufficient power and sensitivity for transmitting and receiving information. Its operating frequency band is acceptable for transmission and reception of an information signal via a waveguide line.

The obtained analytical expressions for calculating the transmission coefficient in comparison with the known ones were characterized by a higher accuracy due to the use of a more accurate value of the characteristic impedance of the transmission line.

The calculation results showed (Fig. 5, 6) that with the piercing path of maximum length, the damping coefficient of the information signal in the proposed modular waveguide did not exceed 83 dB. An increase in the length of the waveguide line by increasing the number of steel bars of the piercing unit leads to a linear increase in the transmission (damping) coefficient of the information signal. In this case, non-uniformity in the waveguide communication line caused by joints between bars does not significantly affect its value. For example, with a line length of 50 m, the coefficient of transmission (damping) increased by 0.8 dB with an increase in the inhomogeneity length Δl to 2 mm and by 1.2 dB with its increase up to 5 mm (Fig. 7, 8).

According to the technical specifications, the dynamic range of the measuring system receiver was at least 85 dB. This means that a small-sized soil piercing unit with bars pushing the piercing head will provide a controlled soil piercing at distances of up to 50 m. Such distances are sufficient for laying utility systems in urban conditions under a road or a tram bed, as well as under various structures.

In contrast to the open line, the level of the signal received via the line did not depend on the route depth, soil composition, and urban structures. In this case, all the transmitter power was spent solely on transmitting the information signal to the receiving point.

The measuring system built according to the proposed principle was more noise-resistant than the known ones since waveguide transmission lines have high noise immunity.

In contrast to the open lines used in practice, it is possible to carry out a controlled soil piercing along the entire length of the piercing track with the help of such a transmission line. This is due to the fact that the reception of the measuring signal from the transmitter is provided continuously and the presence of ground-based obstacles in the path of the route cannot affect the continuity of signal reception.

This approach to constructing a measuring system allows it to be optimized according to the “efficiency-cost” criterion. The use of already developed standard modules reduces the system development time, greatly simplifies its maintenance and personnel training. A combination of the use of relatively cheap modules and the ability to quickly change the configuration in the process of work increases the flexibility of the measuring system.

When amplifying devices are included in the transmitting part of the measuring system as additional modules, the range of controlled soil piercing can significantly increase without additional processing of the inner surfaces of the bars.

Considering that inhomogeneities in the waveguide transmission line cause a change in the plane of wave polarization, the level of the received signal when it changes at the line output can decrease.

To eliminate this drawback, further research envisages the creation of a matching device at the line output which could receive a wave with arbitrary polarization.

It is known that metal bars can change their magnetic permeability under pressure which leads to a change in the transmission coefficient. This phenomenon requires a separate study and currently leads to a limitation of the theoretical studies.

7. Conclusions

1. It has been established that a wave of the main vibration type H_{11} can propagate in bars of small-sized soil piercing units at a frequency of 5 GHz. On this basis, to ensure controlled soil piercing in urban conditions along the entire length of the piercing route, it was proposed to use these bars as a transmission line for the measuring signal.

The structure and circuitry of the measuring system for the 5 GHz frequency have been determined. It is based on industrially produced sensors and modules of Wi-Fi systems which are economical in terms of cost and energy consumption. In particular, a small-sized mini-computer Raspberry Pi 3, model B+ which has a built-in Cypress CYW43455 Wi-Fi transceiver module can be used.

To determine the angles of turning of the piercing head in the horizontal and vertical planes, as well as the angle of rotation of the piercing head around its axis, it was recommended to use the BMX055 spatial position sensor.

The length of the piercing path is determined by the number of extension bars of the piercing unit.

2. The theoretical substantiation of applicability of own metal bars in small-sized piercing mechanisms as transmission lines of the measuring signal was given. Analytical expressions were obtained for calculating the signal transmission coefficient in a non-uniform waveguide transmission line with cascade-connected steel bars of the piercing mechanism. It was found that periodic inhomogeneity in the waveguide caused by the bar joints did not significantly affect its value. For example, damping in the line increased by 1.2 dB at a maximum length of non-uniformity of 5 mm and the total length of the joined bars of 50 m.

It has been established that the range of controlled soil piercing can be at least 50 m when using modules in the Wi-Fi measuring system. Such distances are sufficient for laying utility systems in urban conditions under the roads and tram beds, as well as under various soil structures.

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