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DEVELOPMENT OF A DIAGNOSTIC PROCEDURE FOR ASSESSING THE PERFORMANCE OF A MAGNITOPLANE NAVIGATION SYSTEM

The object of research is the process of ensuring the reliability of high-speed magnetic levitation.

Navigation tasks of high-speed ground transport require high accuracy and reliability along with high speed of obtaining data on the location of the magnetic levitation. The problem to be solved is to ensure the integrity of the magnetic levitation navigation system by means of essential integration into its structure of the diagnostic subsystem, the basis of which is the phase ranging method.

It has been established that the diagnostic procedure for determining the operability of the navigation system of a high-speed vehicle in real time is fully ensured by the use of the phase ranging method. A method of continuous precision positioning of a high-speed magnetic levitation vehicle based on the phase ranging method for an arbitrary configuration in three-dimensional space of a fixed track structure, as well as a method of ensuring the integrity of the navigation system of a maglev train, has been substantiated. A new approach to solving the location problem is proposed, which allows using the train communication channel with the traffic control center as a distributed location sensor as an integral element of the radio wave information and control system.

The structure of the information packet cycle is proposed. The volume of the information flow and the degree of redundancy introduced into the information flow to ensure the required reliability of information transmission are determined.

The developed diagnostic procedure meets the requirements for the safety and reliability of operation of high-speed ground transport based on magnetic levitation technology, the movement of which is controlled using a navigation system topologically connected with the configuration of the track structure.

Keywords: *magnetic levitation transport, phase ranging, navigation, diagnostics, generator, synchronization, signal.*

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1. Introduction

Railway transport was first electrified at the beginning of the 20th century and since then its development has been accompanied by a steady increase in speed [1]. Traditional rail systems have significant physical speed limitations due to the wheel-rail and/or pantograph-contact network. Despite having some of the best cost performance, rail systems are significantly inferior to air transport in terms of speed. The main efforts of researchers and designers of high-speed land transport (HSLT) were aimed at solving the main problem – overcoming the limiting characteristics of the wheel-rail pair. This has led to the creation of vehicles based on the principles of magnetic levitation (maglev), which operate without any mechanical contact with the track structure. Table 1 shows a comparison of speeds for the two types of trains [2].

More recently, the Hyperloop has appeared, which is capable of travelling at speeds much higher than that of a classical maglev and can theoretically break the sound barrier [3]. Although Hyperloop is distinguished as a separate type of transport, it is essentially a maglev travelling in a vacuum tube.

HSLT based on magnetic levitation technology has a complex structure in which several main critical systems are distinguished:

– magnetic suspension, which provides magnetic levitation of the train over the track structure guide. In technical terms, magnetic levitation is usually classified into electromagnetic suspension (EMS) [4] and electrodynamic suspension (EDS) [5]. EDS suspension using a high-temperature superconducting onboard electromagnet is the only passive self-stable suspension system and has a serious potential for high-speed applications;

– a linear traction motor that ensures the movement of a train. Linear traction motors are of two types: linear induction motor (LIM) and linear synchronous motor (LSM) [2];

– magnitoplane motion control system, including diagnostic and navigation subsystems [6];

– a system that provides power to the track structure and on-board systems of the magnitoplane.

Table 1

Comparison of the speed of two types of high-speed land transport

Type of high-speed land transport	Wheel-rail	Magnetic levitation
Record speed, km/h	573.84 (TGV)	603 (L0 series)
Maximum operating speed, km/h	350 (CR Hexie)	428.4 (Shanghai Transrapid)

The overall complexity of HSLT and high traffic speeds place increased demands on the reliability and safety of traffic control systems, which must operate in real time.

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A malfunction is defined as an unacceptable deviation of at least one characteristic property or parameter of a system from the standard operating condition [7]. Faults can cause a loss of control, lead to measurement errors, or change the dynamic properties of the system, which in turn leads to a deterioration in system performance, damage, or destruction [7, 8]. In order to increase the reliability of a system or its individual critical nodes, fault diagnostics is used to monitor, localize and identify faults using the concept of hardware or analytical redundancy. Hardware redundancy is reliable but has a high cost and increases the weight and size of the system, which is sensitive for autonomous systems, so with the development of automatic control theory, the analytical redundancy method has become the main one.

One of the principles of fault-tolerant management is the integration of fault diagnosis into the management process. Over the past decades, considerable experience has been gained in diagnostic methods, fault-tolerant control and their application. Fault diagnostic methods are classified into model-based methods, signal-based methods, knowledge-based methods, hybrid methods, and active diagnostic method [7, 8].

For transport systems, fault diagnosis based on the model method is often used [9].

The experience of designing and operating large information-measuring and information-control systems shows that the processes of control and diagnostics are interrelated when a given level of system reliability indicators is achieved and maintained. HSLT fully belongs to the class of large systems. Methods and means of technical diagnostics ensure finding the cause and location of the detected malfunction of the control object. In maglev transport, the cause of failure can be a wide variety of components, blocks and subsystems. The navigation system of a maglev vehicle is one of the most important, as it provides both a measuring complex of rolling stock parameters and a medium for transmitting critical information to the control center.

Diagnostics of the navigation system state, based on the requirements of fast-moving processes, must also be carried out at speeds commensurate with the processes of maglev vehicle movement relative to the guideway structure of the overpass. The method of motion simulation based on phase ranging can best meet these requirements.

The known concepts and actually operating control systems for highway overpasses are based on radio wave methods [10–12]. In radio-wave methods, part of the motion parameters is determined by means of a magnitoplane with their subsequent transmission via a radio channel to the control center. The other part is transmitted through induction elements built into the track structure. As a rule, in these systems, the presence of an information signal generated by various sensors (position, speed, acceleration, etc.) and a carrier signal that carries information from the sensor to the consumer is fundamental. The information signal always expands the spectrum of the carrier signal in any, even the most efficient, modulation methods. The narrower the frequency spectrum of the modulated carrier signal, the more efficient the communication line is for a given information reception reliability. The efficiency of the communication line can be increased by using the parameters of the carrier signal, for example, its phase characteristics, as information signal. In this case, there is no need for signal modulation and demodulation procedures. The only procedure required is the measurement of those parameters of the carrier signal that are unambiguously related to information about the location of the magnitoplane and other characteristics of its movement.

Such a maglev traffic control system includes several subsystems, including a navigation subsystem, a bidirectional communication subsystem, a train control and diagnostics subsystem, and a photovoltaic distributed power system diagnostics and control subsystem. The proposed control system uses a method based on the measurement of phase shifts between two signals – a reference signal from the control point and an information signal from the moving magnitoplane – to control the movement and transmit information.

Thus, *the aim of this research* is to ensure the integrity of the navigation system of a magnitoplane operating in real time. The integrity of the system is understood as ensuring a given probability of detecting an error within a specified period of time from the moment of its occurrence.

2. Materials and Methods

The object of research is the process of ensuring the reliability of high-speed movement of a magnitoplane.

The analysis of the characteristics of communication transmission lines on waveguides with slotted holes is based on Maxwell's equations. Experimental studies of the characteristics of the functional units of the information and control system and microwave control devices were carried out by measuring the volt-current, amplitude-frequency characteristics, reflection and transmission coefficients. For this purpose, a voltmeter, an ammeter, and a phase difference meter of the FC2-12 type were used.

The concept of building an information and control system as a whole was studied on the basis of decomposition and system analysis methods.

3. Results and Discussion

A specific feature of magnetic levitation transport is the absence of direct contacts with the track structure, hence the need to use contactless methods of information transmission between the magnitoplane and the control point.

The main known technical implementations of contactless systems for determining the position of a moving object are [13]:

1) system in which an electromagnetic wave emitted by a stationary transmitter is received by a moving object, where it is converted into a wave of a different frequency and sent back. The acceleration and velocity of the object is determined at the stationary station by the phase difference between the sent and received waves;

2) system with an inductive sensor, in which the position of the magnitoplane is determined discretely by counting the number of crossings of wires of a special two-wire line laid along the track. This option is implemented in the Transrapid transport system;

3) location system using light signals;

4) inductive location system in which the operating signal is the difference in electromotive forces induced in the magnitoplane antenna by two high-frequency lines;

5) radio wave system in which a main marker-coupled waveguide with groups of communication inlets is placed along the active track structure;

6) inertial navigation system;

7) satellite navigation system;

8) integrated inertial-satellite navigation system.

The characteristic feature of systems 2, 3, 4 and 5 is the counting of the passed markers while the vehicle is moving, with the accuracy of its position determined by the distance between the markers. The second group of systems 1, 6, 7, 8 is based on measuring the time delays of special radio signals propagating between several sources of these radio signals and the magnitoplane. The measurement accuracy in such systems is determined by the wavelength of the emitted signals.

The positioning systems used in existing maglev systems have generally proven to be effective. However, to ensure traffic safety and passenger comfort at high speeds, the requirements for positioning systems are high. For example, for HSLT with speeds of up to 1000 km/h, the navigation system must provide absolute accuracy of up to 10 cm and a level of integrity approaching the level of integrity of avionics systems [13]. Of all the listed non-contact navigation systems, integrated inertial-satellite systems (8) meet the specified requirements in terms of the accuracy of determining the vehicle's coordinates, but have significant limitations in dynamics and when operating in tunnels. The systems based on the phase ranging method fully meet these requirements.

The determination of the magnitoplane coordinates in the proposed HSLT navigation system is based on the method of measuring the phase relations of signals from two synchronized generators. Of these, one serves as a reference and is located in the traffic control center, and the other is an information generator installed on board the vehicle (Fig. 1).

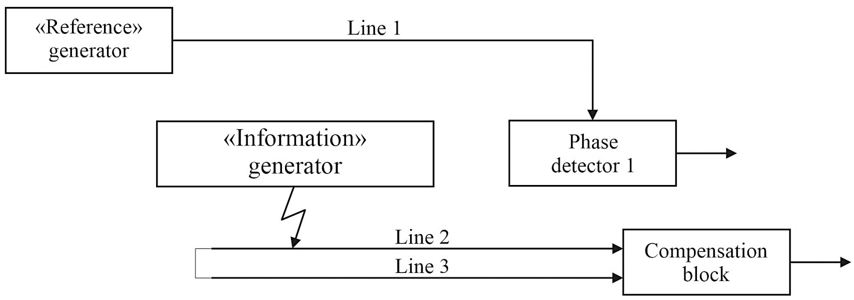

Fig. 1. Block diagram of the phase-metric magnitoplane position sensor

The peculiarity of this approach is the implementation of a continuous process of tracking the location of the magnitoplane on the track, i. e., in real time. The required accuracy is achieved by selecting the appropriate frequency of the generators. A fundamental limitation of the phase ranging method is the maximum speed of electromagnetic wave propagation in the medium, in particular in a coaxial slot line. All known HSLT navigation systems (Transrapid, RJ-maglev) have a discrete nature of operation, the accuracy of which is limited by the size of the discrete.

The signals from both generators are transmitted via different communication lines to the control center, where their phase difference is measured. Due to the synchronous oscillations of the generators, the phase difference at the point of reception will depend on the distance between the control point and the magnitoplane moving with the 'information' generator on board and, accordingly, is uniquely related to the location of the magnitoplane on the track. The unambiguity of measurements is ensured by the choice of frequencies. The generation frequency of both generators should be chosen so that the wavelength is equal to the distance between the two stations, i. e., the length of the run. If the length of the run is taken to be within a few tens of kilometers, the frequency will be equal to several kilohertz. At such frequencies, difficulties are inevitable due to the technical feasibility of optimally matching the size of the emitter on the magnitoplane and the slot line.

Therefore, it is worth considering the option of using two microwave signals (signals with an ultra-high frequency bandwidth) with a frequency shift by an amount corresponding to a certain frequency f_1 with a wavelength equal to the length of the run. If the maglev vehicle is at the beginning of the track (standing at the station), the phase shift is zero, which corresponds to a zero path. If it has travelled a quarter of the track length, the phase shift will be 90°, half of the track length will be 180°, three quarters will be 270°, and the entire track length will be 360°. The accuracy of the train location is determined by the initial synchronization and the instrumental accuracy of the phase calculation unit.

Synchronization of generators is carried out by means of the satellite radio navigation system (SRNS). This system makes it possible to synchronize generators with resulting frequency instability of up to 10^{-14} [14]. The standard error in the measured phase of synchronized generators during the day is 15–30 ns, as a result of which the error in determining the position of the magnitoplane on the run due to non-synchronism will not exceed 5–10 cm. The procedure for bringing the generators into synchronization is implemented automatically during train stops at stations in accordance with the algorithms provided by SRNS.

Since the speed of obtaining data on the signal phase difference is much higher than the speed of the vehicle, the method allows obtaining data on the parameters of the magnitoplane movement in real time. In addition, the method provides data on the axial displacement and air gap between the track structure and the magnitoplane. For this purpose, the phase difference of signals coming from the same 'information' generator but along different trajectories is measured (Fig. 2). Each of the signals, before reaching the measuring circuit in the control room, passes through a small section between the magnitoplane and the transmission line, the length of which depends on the degree of deviation of the train from the centerline and the size of the vertical gap.

The considered elements of hardware, information control and diagnostics are an integral part of the navigation system and are shown in blocks in Fig. 3.

The time diagram of the monitoring and diagnostics system is shown in Fig. 4.

The navigation system control and diagnostics procedure are carried out both in the allocated time resource mode in the information frame of 384 μs duration at intervals of 7232 μs, and during periods of vehicle absence on the track. Hardware monitoring and diagnostics of lines 1 and 2 is performed by sending a 214 μs test signal to the lines of the magnitoplane motion simulator. The control and diagnostics processor at the output of lines 1 and 2 analyses the status of all line nodes according to the "working-unworking" criterion. A window of 384 μs is allocated for the test signal, but the test signal itself has duration of 214 μs in order to have time to travel the length of a track during the window and thus not interfere with the information signals. The structure of the test signal is chosen so that the analysis at the line output allows detecting malfunctions in the operation of cable sections, controlled amplifiers and phase shifters. In addition, each amplifier and phase shifter provides information about its own performance to the interface. Thus, the monitoring system covers all nodes of communication lines 0, 1 and 2.

The "information" generator on board the magnitoplane is an integral part of the navigation system, and its performance, along with other radio equipment, is also subject to continuous monitoring by the maglev vehicle control equipment. Information about the results of monitoring and diagnostics is transmitted in each frame received on lines 1 and 2 for 2048 μs with a period of 7232 μs and occupies a space of 26 bits. Thus, the control and diagnostics processor receives data on the status of all components of the magnitoplane in real time.

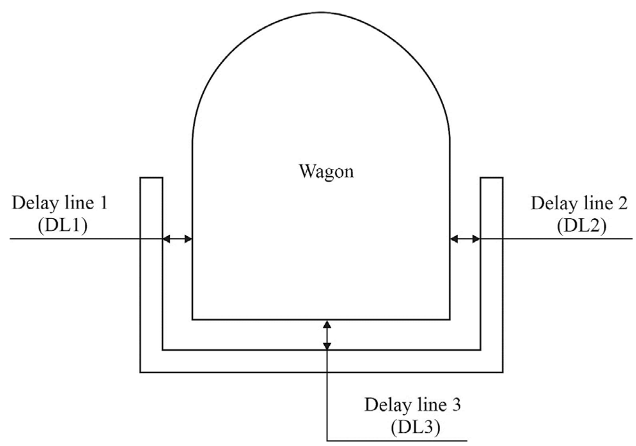

Fig. 2. Variable delay lines

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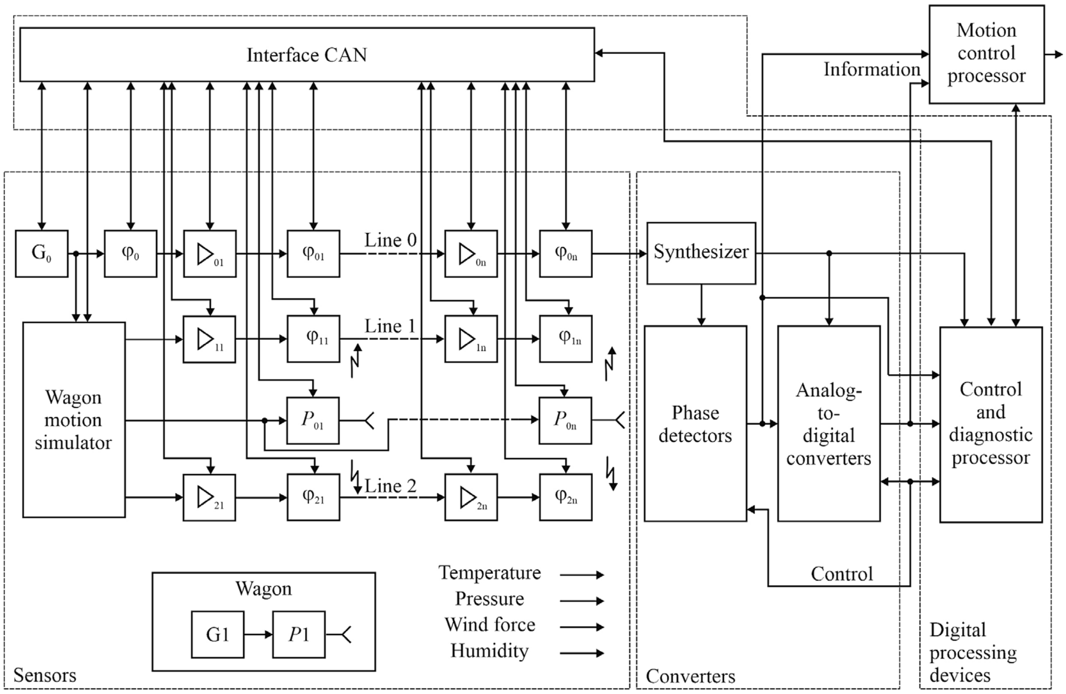

Fig. 3. Block diagram of hardware and functional control of the navigation system

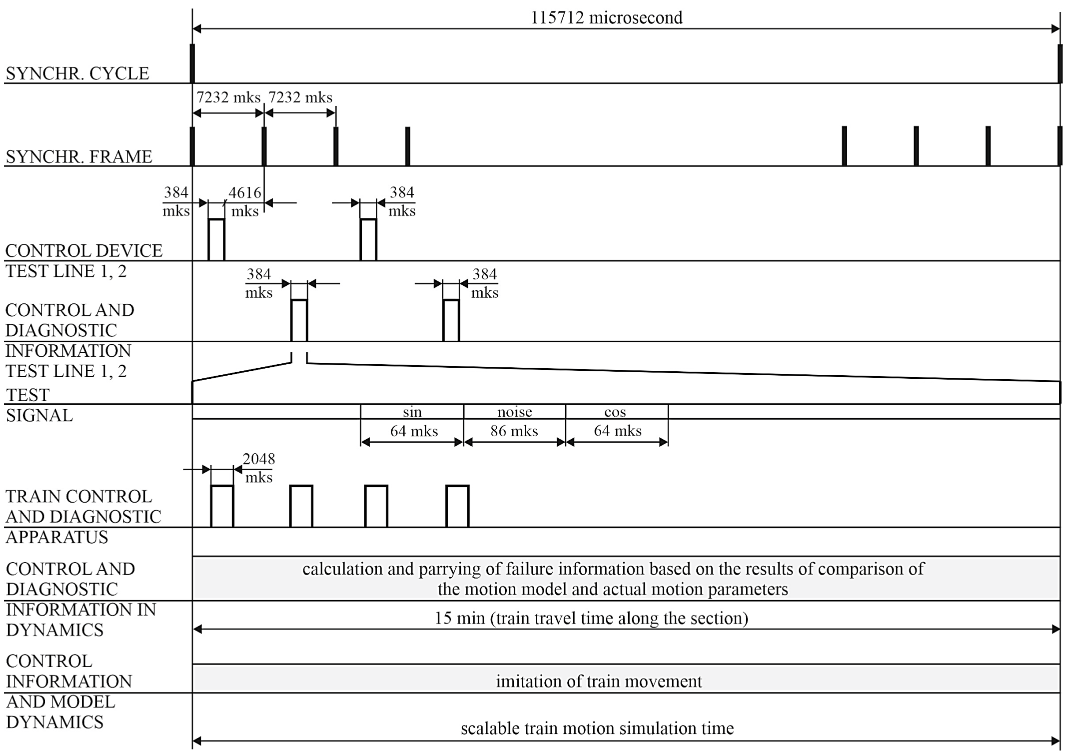

Fig. 4. Time diagram of the monitoring and diagnostics system

As noted above, the procedure for controlling and diagnosing information is designed to detect an error in the production of a navigation parameter outside the established tolerance. In this navigation system, this task is solved by a step-by-step comparison of the measured navigation parameters with a dynamic model of the magnitoplane movement along the track structure trajectory along the entire length of the run. The model takes into account the schedule of movement along the track, coordinate features of the track structure (straight and curved sections, ascents, inclines), dynamic parameters of the maglev vehicle (size, weight, aerodynamics), weather conditions on the track (air temperature, pressure, wind strength and direction, humidity, precipitation, air density). The model also receives information about the energy supply of the track structure. The use of such a model makes it possible to obtain current errors of navigation parameters and predict unfavorable trends in their development, which in turn is used to parry information failures. The proposed procedure and architecture of control and diagnostics also provides for the possibility of using these tools for the tasks of adjusting the navigation system at the stages of installation and adjustment of the track structure and monitoring the functioning of the entire traffic control system. For this purpose, controlled reference signal sources are installed at each amplification section. At the same time, the maglev vehicle motion simulator generates and transmits signals to lines 1 and 2, which will be perceived as information signals from the magnitoplane at the output of the lines. This simulation allows for the most complete control of the HSLT navigation system performance.

The signal from the "reference" generator is transmitted to the control center via a separate cable laid along the track structure, while the signal from the "information" generator is transmitted via two coaxial slotted communication lines, which are also laid along the track structure. A coaxial slot line is formed by two cylindrical conductors placed one inside the other. The outer conductor has a slit along its entire length, which allows for the contactless transmission of electromagnetic radiation from the "information" generator to the communication line.

The information received at the control point about the position of the magnetic circuit on the run is used to generate control signals for the 'short' traction sections of the maglev transport track structure [15].

The task of controlling and diagnosing the precision navigation system of a maglev vehicle should be considered as an integral part of a system-wide approach to ensuring the strategy for managing the performance and safety of maglev vehicles. Information about the state of the navigation system is formed by technical means of monitoring and diagnosing information failures, where control means detection of a failure and diagnosis means its localization. Thus, the control and diagnostics subsystem are a navigation system signature control system, i. e., a system of symbols and unambiguous rules for their interpretation to represent information in the form of data.

The procedure for monitoring and diagnosing the navigation system performance is as follows.

The simulation signal is a microwave signal fed into lines 1 and 2 (Fig. 3) and synchronized with the signal coming into line 0 from the precision generator G_0. The signal from the motion simulator is similar to the signal of the magnitoplane when the magnitoplane is moving. The difference is that the digital processing device on the receiver side measures the phase difference between lines 1, 2 and line 0 within the selected wavelength of the test signal. The test signal has a frequency of about 300 MHz, so the wavelength does not exceed one meter.

By changing the signal delay in the simulator relative to the signal from the generator G_0, it is possible to diagnose the integrity of all three lines and the presence of signals at their outputs. By varying the initial phase delay within 360°, it is possible to simulate the position of the magnitoplane at the beginning of the track within the wavelength of the signal coming from the generator G_0. In this case, the rate of change of the phase delay simulates the speed of the magnitoplane at a distance within the wavelength and only at the beginning of the track. It's not possible to simulate a phase shift over a distance greater than a wavelength by using phase delays between signals alone. In order to unambiguously simulate the effect of a magnitoplane's movement over a 50 km run, it is necessary to use the so-called radio frequency jitter phenomenon. Radio frequency jitter occurs when two periodic oscillations, for example, harmonic oscillations, are superimposed and manifested in a periodic decrease and increase in the amplitude of the total signal. The frequency of change in the amplitude of the total signal is equal to the difference in the frequencies of the original signals.

Jitter occurs when one of the signals is linearly out of phase with the other. At those moments when the oscillations are in phase, the total signal is maximized, and at those moments when the two signals are out of phase, they cancel each other out. These moments periodically replace each other as the lag increases.

The simulation process is based on the fact that at close values of the precision frequencies, the measured difference and their phase will change at a rate determined by the beat frequency, which is equivalent to the effect of the magnitoplane movement. For a 50 km long run with a speed of 500 km/h, the travel time is 6 minutes. In order to simulate such a movement (the phase between the two oscillations must change by 360° in 6 minutes), it is necessary to set the difference in precision synchronized frequencies to approximately 0.00277 Hz or less. With such a difference, the phase reference will be unambiguous. If the frequency difference is less than the specified value, it will be equivalent to simulating the movement of the magnitoplane at a lower speed. This solution allows to simulate the movement of the vehicle in the entire speed range and for any length of the track. If a number of radiation devices (low-power generators) synchronized in frequency with the generator G_0, are installed on the track structure of the track, the problem of simulating the magnetic circuit stopping in certain sections of the track is solved. At the same time, the problem of localizing a cable fault with an accuracy of several hundred meters is solved. In Fig. 3, such radiation devices are labelled as $P_{01}...P_{0n}$. According to a pre-arranged time sequence, the radiation devices generate radio frequency signals in line 1 and 2.

Each radiating device has precise range coordinates that are unambiguously linked to phase measurements, for example, a magnitoplane standing somewhere on the track. By switching on the radiation devices sequentially and measuring the phase, the position of the train on the track can be simulated.

The simulation of the magnitoplane's movement allows for both operational diagnostics of the navigation system's integrity and in-flight monitoring. On-the-fly monitoring is possible because the cable bandwidth allows the use of two precision frequencies simultaneously, followed by selection on the receiver side with satisfactory resolution. This makes it possible to select the frequency and phase parameters of the second frequency in such a way that it's possible to simulate the movement of another magnitoplane moving ahead.

The simulated motion signal of the maglev vehicle is also intended to verify the operability of the control circuits of all autonomous photovoltaic units within the distributed photovoltaic power system [16, 17]. Each traction-levitation module of the guideway structure, on which the corresponding photovoltaic unit operates, is equipped with an individual magnetic field sensor. The simulated motion signal, when analyzed at the control room, allows the maglev vehicle to simulate the position of the maglev vehicle on the track. In accordance with the position coordinates, the photovoltaic system sends a voltage signal to the traction and levitation module connected to this system. This triggers the magnetic field sensor of this module and the signal from it is returned to the control center. The received signal is used to make a decision on the operability of the photovoltaic system and the traction and levitation module. Since several traction and levitation modules must be activated simultaneously to cover the length of the magnitoplane, this checks the synchronization of the virtual maglev vehicle's movement and the operation of the corresponding traction and levitation track modules along the entire track.

The simulation signal is used to simulate the following parameters of the magnitoplane movement:

- position of the maglev vehicle in relation to the pole division of the traction linear motor [15];
- the position of the maglev vehicle on the track;
- direction of movement;
- maglev vehicle speed;
- direction, magnitude, speed and acceleration of the transverse displacement;
- direction, magnitude, rate of change, acceleration of change in the air gap between the maglev vehicle and the track structure.

For this purpose, when simulating the motion of the magnitoplane in strictly defined time intervals, the simulated signal is phase-modulated within the known range of phase change. The phase change depends on the deviation of the maglev vehicle from the axis line of the track structure in the horizontal plane and the distance to the track structure in the vertical direction.

The navigation system with a built-in motion simulation function allows for multiple checks of the integrity and functioning of the entire system in a short time. This opens up the possibility of forming a large database on the stability of the phase characteristics of the entire diagnostic system, which in turn can serve as the basis for predicting a guaranteed period of trouble-free operation.

The fundamental limitation when creating a system for determining the position of a magnetic plane relative to the track structure based on the phase ranging method is the maximum propagation speed of an electromagnetic wave in the medium, in particular in a coaxial slot line. However, given that the propagation speed of an electromagnetic wave is much higher than the speed of the vehicle, this limitation does not affect the reliability of obtaining data on the phase difference of signals.

A possible direction for the development of this research could be a directional communication line based on a radio-emitting cable, as a further development of the slot coaxial line.

4. Conclusions

According to the results of the study, it can be stated that the diagnostic procedure for determining the performance of the navigation system of a high-speed vehicle in real time is fully ensured by the use of the phase ranging method, which is the basis for simulating the movement of the magnitoplane. The developed control and diagnostic procedure meets the requirements of safety and reliability of the magnitoplane operation, the motion of which is controlled by a navigation system topologically linked to the configuration of the track structure.

A method of continuous precise positioning of a high-speed magneto-levitating vehicle based on the method of phase ranging for an arbitrary configuration in the three-dimensional space of a fixed track structure using the train communication channel with the traffic control point as a distributed location sensor as an integral element of the radio wave information and control system is substantiated.

The structure of the cycle of the information package is proposed. The packet consists of monochromatic signal parcels, which are used to calculate the phase, and a frame of phase-manipulated parcels that carry information about the functioning of the magnitoplane systems. The volume of the information flow and the degree of redundancy introduced into the information flow to ensure the required reliability of information transmission are determined.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

The manuscript has no linked data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of the current work.

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