Rubric 2: SCIENTIFIC AND PRACTICAL DEVELOPMENTS
Field “Electrical Engineering”

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LEVITATION CHARACTERISTICS OF ELECTRODYNAMIC SUSPENSION TRANSPORT RUNNING ON GUIDEWAY WITH LONGITUDINAL JOINT

Aim: to propose a technical solution to ensure the lateral stabilisation of the vehicle with an electrodynamic suspension. Development of a method for calculating the levitation characteristics of a transport unit with an electrodynamic suspension running on a guideway with a longitudinal joint. Analysis of the results of theoretical studies.

Methods: in the article, the methods of the electromagnetic field theory, generalised functions, Fourier transform, analytical and numerical methods for determining quadratures are used. The software was developed in the Fortran language.

Result: to ensure lateral stabilisation of the vehicle with an electrodynamic suspension, it was proposed to introduce a longitudinal insulating joint into the structure of the guideway. A mathematical model is proposed for this system of electrodynamic suspension in approximation of an infinitely wide track structure of rectangular cross section.

For the ultimate case when the width of the joint tends to zero, and the vehicle electromagnets have a rectangular form based on the application of the Fourier transform, the solution of the equations was obtained describing the adopted mathematical model: the expression of the vector of magnetic induction and electrodynamic force in the quadrature. Numerical integration of these equations was performed by applying the Gauss formula and the Philo method.

The results of the calculations allowed us to obtain a number of graphical dependencies of the levitation characteristics on the value of the lateral displacement of the vehicle electromagnet relatively to symmetrical position.

Conclusion: thus, the obtained results of the study fully meet the goal of determining the parameters of the laterally stabilising the electrodynamic vehicle with the guideway equipped with a longitudinal joint under the assumptions made. Comparison of the proposed method with other proposed stabilisation methods does not reveal the decisive advantages or disadvantages of the new method. In most cases, its most serious weakness is its *relatively* low levitation quality. However, it is significantly reduced if the movement of the high-speed ground transport occurs predominantly at high speed, at which the force of aerodynamic drag prevails over the force of electrodynamic braking.

Of the same relativity is the advantage of the system proposed, that is *great lateral rigidness*. The reason for this is that the requirements to the *lateral rigidness* can be formulated quantitatively only in relation to the particular high-speed ground transport line, taking into account the traffic schedule and other factors. As it is known, the main destabilising influences in lateral direction are the inertia at curves and lateral wind. The tasks solved by other subsystems of the high-speed transport line, can play their certain role in

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choosing of the stabilisation system as well. It is clear from the above that the final decision on the stabilisation system at this stage of research would be premature. The new stabilisation method suggested and studied in this paper should be considered only as another possible together with the earlier proposed one. The answer to the question about the competitiveness of the new method should be related to the characteristics of the particular high-speed ground transport line. Further specification of the results is required considering the edge effect, as well the uninsulated joint case.

Keywords: transport unit, electrodynamic suspension, longitudinal joint, lateral stabilisation, electromagnetic characteristics, generalised functions, Fourier transform.

Рубрика 2. НАУЧНЫЕ И ПРАКТИЧЕСКИЕ РАЗРАБОТКИ
Направление «Электротехника»

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ЛЕВИТАЦИОННЫЕ ХАРАКТЕРИСТИКИ ТРАНСПОРТНОЙ УСТАНОВКИ С ЭЛЕКТРОДИНАМИЧЕСКИМ ПОДВЕСОМ ПРИ НАЛИЧИИ ПРОДОЛЬНОГО СТЫКА В ПУТЕВОМ ПОЛОТНЕ

Цель: предложить техническое решение, позволяющего обеспечить боковую стабилизацию экипажа с электродинамическим подвесом. Разработка метода расчёта левитационных характеристик транспортной установки с электродинамическим подвесом при наличии продольного стыка в путевом полотне. Анализ результатов теоретических исследований.

Методы: в статье использовались методы теории электромагнитного поля, обобщенные функции, преобразование Фурье, аналитические и численные методы определения квадратур. Программа для ПЭВМ разрабатывалась на языке Фортран.

Результаты: для обеспечения боковой стабилизации экипажа с электродинамическим подвесом предложено ввести в структуру путевого полотна продольный изоляционный стык. Создана математическая модель исследуемой системы электродинамического подвеса в приближения бесконечно широкого полотна прямоугольного сечения.

Для предельного случая, когда ширина стыка стремится к нулевому значению, а экипажные электромагниты имеют прямоугольную форму на основе применения преобразования Фурье получено решение уравнений, описывающих принятую математическую модель: выражение вектора магнитной индукции и электродинамической силы в квадратурах. Численное интегрирование этих уравнений выполнялось посредством применения формулы Гаусса и метода Филона.

Результаты расчетов позволили получить ряд графических зависимостей левитационных характеристик от величины бокового смещения экипажного электромагнита относительно симметричного положения.

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Заключение: полученные результаты проведенного исследования полностью отвечают поставленной цели по определению параметров боковой стабилизации экипажа с электродинамическим подвесом с путевым полотном, содержащим продольный стык в рамках принятых допущений. Сравнение предложенного способа с другими предлагавшимися ранее способами стабилизации не позволяет выявить решающих преимуществ или недостатков нового способа. В большинстве случаев его недостатком является *относительно* низкое левитационное качество. Однако оно существенно возрастает, если движение экипажа ВСНТ происходит преимущественно с высокой скоростью, при которой сила аэродинамического сопротивления превалирует над силой электродинамического торможения.

Столь же относительным является и достоинство рассматриваемой системы – *высокая боковая жёсткость*. Причина этого в том, что требования на боковую жёсткость могут быть количественно сформулированы лишь применительно к *конкретной трассе* ВСНТ с учётом графика движения и других факторов. Как известно, главными дестабилизирующими воздействиями в боковом направлении являются сила инерции при движении по криволинейному участку и боковой ветер. Свою роль в выборе системы стабилизации могут сыграть и задачи, решаемые другими подсистемами системы ВСНТ. Играет определенную роль также принцип действия и конструкция системы тяги. Из сказанного ясно, что окончательный выбор системы боковой стабилизации на настоящем этапе исследований был бы преждевременным. Предложенный и изученный в этой статье новый способ стабилизации следует рассматривать как ещё один из возможных наряду с предлагавшимися ранее. Ответ на вопрос о конкурентоспособности нового способа должен быть связан с характеристиками конкретной трассы ВСНТ. Необходимо и дальнейшее уточнение результатов, при более строгом учёте краевого эффекта, а также рассмотрением случая неизолированного стыка.

Ключевые слова: транспортная установка, электродинамический подвес, продольный стык, боковая стабилизация, электромагнитные характеристики, обобщенные функции, преобразование Фурье.

INTRODUCTION

For a majority of industrial developed countries consistent passenger transit growth is inherent, which can be ensured through increase of capacity and throughput of transport systems. At the same time, transport services quality is supposed to be enhanced: reduction of time costs of door-to-door delivery, reduction of rolling stock occupancy rate in rush hours, and shortening of headways.

One of the alternative answers to this challenge is construction of high-speed ground transport systems (HGTS) using magnetic suspension. Construction of magnetic suspension HGTS fosters economic growth through implementation of cutting edge results of technical and scientific progress, and encourages strengthening of Russia’s prestige as one of the leading countries with highly-developed transport systems [1–5].

Two types of magnetic suspension are primarily used – electromagnetic (EMS) and electrodynamic (EDS) suspensions.

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EDS system is based on repulsive forces, emerging between magnetic field of superconducting DC electromagnets onboard of the vehicle and currents induced by them in a continuous or discrete type of guideway. In comparison to EMS, EDS provides a larger suspension height (100–200 mm). EDS inherently has a natural vertical stability.

There are many ways to achieve lateral stabilisation of EDS transport systems' vehicles. However, each of them has its own certain disadvantages. In this regard, it is relevant to find an alternative method for the lateral stabilisation of the vehicle of this transport system.

The aim of this work is to obtain theoretical and technical solutions that ensure achievement of this aim.

MAIN DEFINITIONS AND TASK SETTING

The design of EDS system, the guideway of which has a longitudinal joint, is presented in Fig. 1.

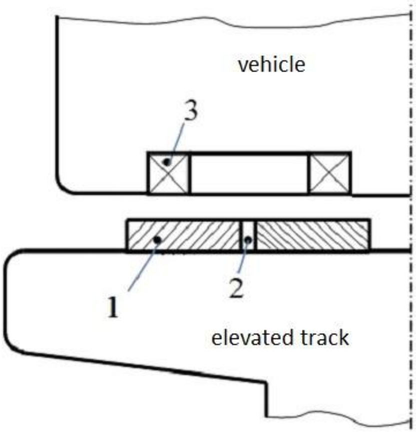

Fig.1. Design of EDS transport system having longitudinal joint in the guideway

Fig. 1 shows: 1 – guideway, 2 – longitudinal joint in the guideway, 3 – suspension electromagnet.

The calculation scheme for levitation characteristics of transport unit with EDS system having a longitudinal joint is given in Fig. 2.

Let us proceed from the assumption that the presence of the longitudinal joint in the guideway will provide stability lateral stability to EDS.

To substantiate this assumption, let us limit ourselves to the approximation of an infinitely wide guideway.

We will assume that the guideway is a layer between the planes $z = 0$ and $z = T$ (T – thickness of the guideway), the air gap in the guideway occupies the area $-a < y < a$ (thus, the width of the air gap is $2a$), the vehicle onboard electromagnet moves along the axis x in the plane $z = h > T$.

In [6] *the method of assumed boundary* is suggested that enables bringing the task of calculation of electromagnetic field in the described system to

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calculation of the fields excited in the plane layer $0 \leq z \leq T$, fully filled with non-homogeneous conductive medium. For this case the specific conductivity of the medium in this layer depends only on the coordinate y, and this dependence has the form of (1):

$$\sigma(y) = \sigma_0 k(y),\; k = \begin{cases} 1 at\, |y > a| \\ 0\; at\, |y < a| \end{cases}. \tag{1}$$

Here, σ_0 – specific conductivity of the guideway material.

The calculation diagram for determination of levitation properties of the transport unit with EDS having a longitudinal joint in the guideway is given in Fig. 2.

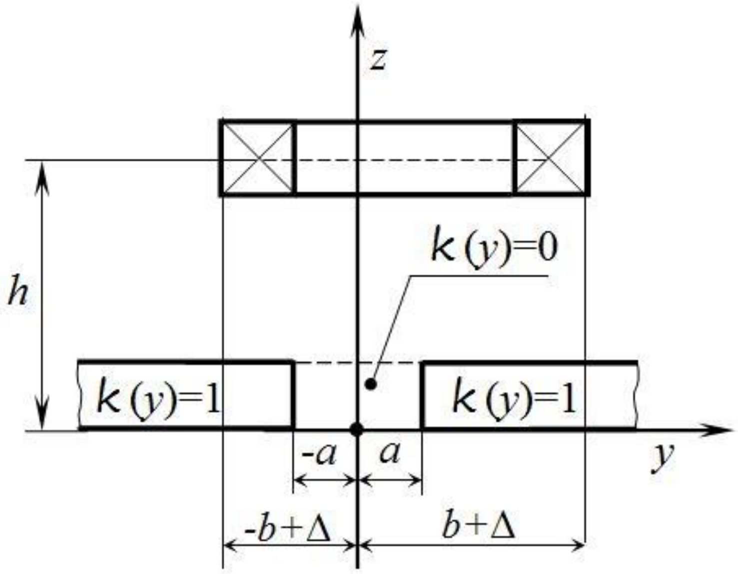

Fig. 2. Calculated diagram of EDS transport system
with a longitudinal joint in the guideway

The problem of calculation of fields in the non-homogeneous conducting layer, the specific conductivity of which can depend on all three coordinates, is considered in [7], where the basic integral equation of the EDL theory is obtained, in which the role of the unknown function is played by the Fourier-image of the vector of electrical field strength ***E*** in the layer $0 \leq z \leq T$.

In [8] the specific case (transverse joint) is covered in detail, when the specific conductivity depends only on the coordinate x, and this dependence has the form (1) with y replaced by x. It is shown that with real values of parameters of the system, the approximation of the thin guideway (skin layer thickness is larger than that of the guideway) is applicable, and in this approximation one dimensional integral equation for Fourier image of x-component of the vector ***E*** has been obtained.

Repeating these considerations as applied to the longitudinal joint, we can obtain the following integral equation of the Fourier-image of y-component of the vector ***E***.

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$$u(y) = \Phi(y) + \frac{i\xi}{\pi r}\int u(y')\left[K_0(|\xi(y-y')|) - H(y)K_0(|\xi(y'-a)|) - \right.$$
$$\left. - H(-y)K_0(|\xi(y'+a)|)\right]dy' \ . \qquad (2)$$

Here, $u(y)$ – the Fourier-image E_y by the variable x; ξ,η – Fourier transform parameters by variables x and y; $k = \xi \boldsymbol{e}_x + \eta \boldsymbol{e}_y$, $k = |k| = \sqrt{\xi^2 + \eta^2}$; $\Phi(y) = f(y) - H(y) f(a) - H(-y) f(-a)$; $f\ (y)$ – the Fourier inversion of the function $f(\eta) = (\mu_0/2k)v\xi^2 V(k)e^{-kh}$; $r = 2/l$; $l = \mu_0\sigma_0 vT$; v – vehicle velocity, $V(k)$ – the Fourier-image by x and y of potential current function, characterising the form and force of the vehicle electromagnet [9];
$H(y) = \begin{cases} e^{-|\xi y|}/(2\mathrm{ch}(\xi a) & y > a \\ 0 & y < -a \end{cases}$; K_0 – modified Hankel function of the zero order [10]. While obtaining this equation, the data in [11] were also used.

LEVITATION CHARACTERISTICS CALCULATION

Let us limit ourselves to the case when the width of the air gap 2*a* is smaller as compared to other typical sizes of the system. In this case, the influence of the joint is mainly connected not with absence of the conductive medium in the air gap $|y| < a$, but with distortion of the eddy current picture in the guideway, which is caused by the absence of electrical contact between the areas $y > a$ and $y < -a$. For this reason, the equation (2) can be replaced by its ultimate case with $a \to 0$, i.e. by equation:

$$u(y) = f(y) - f(0)e^{-|\xi,y|} + \frac{i\xi}{\pi r}\left[\int_{-\infty}^{\infty} K_0(|\xi(y-y')|)u(y') - e^{-|\xi,y|}\int_{-\infty}^{\infty} K_0(|\xi\, y|)u(y)\,dy\right] (3)$$

The equation (3) is solved in quadrature. For this purpose, it is convenient to make in the equation (3) Fourier transform by variable *y*. The first integral in the formula (3) is the convolution by variable *y*, and the second - the scalar multiplication in the space $L_2(-\infty<y<\infty)$ of the functions $K_0(|\xi y|)$ and $u(y)$, therefore as the result of Fourier transform they will consequently turn to multiplication and scalar multiplication in $L_2(-\infty<\eta<\infty)$ of the Fourier-images of the given functions. Expressing the value $f\ (0)$ through the Fourier-image of the function *f* and using data [11], the following equation can be obtained from (3)

$$u(\eta) = f(\eta) - \frac{|\xi|}{\pi k^2}\int_{-\infty}^{\infty} f(\eta)\,d\eta + \frac{i\xi}{r}\left[\frac{u(\xi)}{k} - \frac{|\xi|}{\pi k^2}\int_{-\infty}^{\infty}\frac{u(\eta)}{k}\right].$$

Having separated *u* here, which stands outside the integral, we come to integral equation with degenerate kernel, which is solved with standard method [12, 13, 14], and the solution of which has the form

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$$u(\eta) = \frac{r}{kr - i\xi}\left[kf(\eta) - \frac{\gamma|\xi|\int\limits_{-\infty}^{\infty} kf(\eta)/(kr - i\xi)d\eta}{k(\pi + i\,\mathrm{sign}(\xi)\ln(\lambda+1)/(\gamma\text{ -}1)} \right];\;\; \gamma = \sqrt{r^2+1}. \tag{4}$$

Let us reiterate that the *u* function is the *y*-component of the sought vector ***E***. Knowing it, we can find all the vector components. Its *x*-component is defined by the following expressions ***E*** and ***B*** [8]. Then, using the approach [9], in the similar manner as it was done in [8], we can find the force acting on the vehicle electromagnet.

Omitting the intermediate conclusions, we give the resulting formulas, determining this force

$$\boldsymbol{F} = \boldsymbol{F}_0 + \boldsymbol{f}\;;\;\; \boldsymbol{F}_0 = 4\mu_0 l\left(\frac{l}{2}\boldsymbol{e}_z - \boldsymbol{e}_x\right)\int\limits_0^{\infty} d\xi \int\limits_0^{\infty} d\eta \frac{k^2\xi^2 e^{-2kh}|V(\boldsymbol{k})|^2}{4k^2 - i^2\xi^2}, \tag{5}$$

$$\boldsymbol{f} = \frac{\mu_0\gamma}{2}\int\limits_{-\infty}^{\infty} d\xi \frac{\xi^2}{i\pi\,\mathrm{sign}(\xi) + \ln\dfrac{\gamma+1}{\gamma\text{ -}1}}\left\{\int\limits_{-\infty}^{\infty} d\eta_1 \boldsymbol{G}_1^- \frac{e^{-k_1 h}\boldsymbol{V}(\boldsymbol{k}_1)}{k_1 r - i\xi}\int\limits_{-\infty}^{\infty} d\eta_2 \frac{e^{-k_2 h}\boldsymbol{V}(\boldsymbol{k}_2)}{k_2 r - i\xi}\right\} \tag{6}$$

$$\boldsymbol{k}_{1,2} = \xi\boldsymbol{e}_x + \eta_{1,2}\,\boldsymbol{e}_y;\;\; k_{1,2} = |\boldsymbol{k}_{1,2}|\;;\;\; \overrightarrow{\boldsymbol{G}}_1^- = i\xi\boldsymbol{e}_x + \eta_1\boldsymbol{e}_y - k_1\boldsymbol{e}_z.$$

Let's specify the received relations with reference to a case of the rectangular form of a vehicle electromagnet with a length 2*a* and width 2*b*. Its lateral displacement relative to the plane *y* = 0 will be indicated by Δ (see Fig. 2). For the described case

$$V(k) = \frac{2I}{\pi}\frac{\sin a\xi \cdot \sin b\eta}{\eta\xi}e^{-i\eta\Delta}.$$

Putting it into the equation in (6), we can obtain after a number of elementary transformations

$$\begin{cases} \boldsymbol{f}_x = C\int\limits_0^{\infty}\xi\sin^2(a\xi)\,\mathrm{Im}(\alpha I_1)\,d\xi;\;\; \boldsymbol{f}_y = C\int\limits_0^{\infty}\xi\sin^2(a\xi)\,\mathrm{Re}(\alpha I_1 I_2)\,d\xi; \\ \boldsymbol{f}_z = C\int\limits_0^{\infty}\sin^2(a\xi)\,\mathrm{Re}(\alpha I_1 I_3)\,d\xi;\;\; \partial\boldsymbol{f}_y/\partial\Delta = C\int\limits_0^{\infty}\sin^2(a\xi)\,\mathrm{Re}(\alpha(I_1 I_4 - I_2^2))\,d\xi. \end{cases} \tag{7}$$

Here, $C = \dfrac{16\mu_0\gamma I^2}{\pi^2}$; $\alpha = \left(\ln\dfrac{\gamma+1}{\gamma-1} + i\pi\right)^{-1}$; $I_i(\xi)\int\limits_0^{\infty}\dfrac{J_i(\xi)\sin(b\eta)}{kr - i\xi}e^{-kh}\;(i = 1,\ldots 4)$;

$$J_1(\eta) = \cos(\Delta\eta)/\eta;\;\; J_2(\eta) = \sin(\Delta\eta)\;;\;\; J_3(\eta) = k\,J_1(\eta)\quad J_4(\eta) = \eta\cos(\Delta\eta)\;.$$

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The value $\partial f_y/\partial\Delta$ has the sense of lateral rigidity of the suspension, its expression is obtained by differentiation of the formula for f_y.

Putting the above-given expression for *V (k)* into the formula (5) leads to its cardinal simplification: transiting in the integral (5) to the polar coordinates k, φ ($\xi=k\cos\varphi$, $\eta=k\sin\varphi$) it is possible to notice that the integral by *k* is calculated analytically, as a result of which the formula for the electrodynamic force $\boldsymbol{F_0}$ acquires the following form

$$\boldsymbol{F}_0=\frac{\mu_0 l}{\pi^2}\left(\frac{l}{2}\boldsymbol{e}_z-\boldsymbol{e}_z\right)\int\limits_0^{\pi/2}\ln\left\{\frac{(1+A^2\cos^2\varphi)^2(1+B^2\sin^2\varphi)^2}{(1+(A\cos\varphi+B\sin\varphi)^2)(1+(A\cos\varphi-B\sin\varphi)^2)}\right\}\times$$

$$\times\frac{d\varphi}{\sin^2\varphi(4+l^2\cos^2\varphi)} \tag{8}$$

Here, A = *a/h*, B = *b/h*.

NUMERICAL CALCULATION METHOD

To perform certain calculations using the presented formulas, there is one thing left, i.e. to rationally choose the method of numerical integration. The calculation of the integral (8) does not bring about any difficulties. For this, any simple quadrature formula can be used. In fact, the Gauss formula with ten and twenty-four (depending on certain values of the parameters) nodes was used.

The calculation of the integrals, contained in (7), is more complex, due to infinity of the integration interval and fast oscillation of sub-integral function. For calculation of the integrals of this type, it is relevant to use the Philo method [15]. Let us note that in the sub-integral expression for $I_1(\xi)$ there is a removable peculiarity: sin $b\eta$, therefore, in calculation of this integral using the Philo method, it is necessary to separate some small area of zero, and the integral for this area should be calculated individually.

ANALYSIS OF THE CALCULATION RESULTS

The results of the calculations performed are given in Fig. 3, 4. All charts in these figures reflect the dependence of levitation characteristics on the value of lateral displacement of the vehicle electromagnet relatively to the symmetrical position. The value of displacement is set in the relative units $\Delta/2b$, where $2b$ – the width of the electromagnet. The calculations correspond to the following set of data: suspension height h = 22 cm, magnet length $2a$ = 1 m, magnet width $2b$ = 30 cm, plate width – 5 mm, specific conductivity of material of the guideway $\sigma = 3.4\cdot10^7$ (Ω·m).

Since the aim of the introduction of the longitudinal joint is in lateral stabilisation of electrodynamic suspension, the lateral, i.e. *y*-component of the

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levitation force is of greatest interest. The dependence of this component on the displacement value is given in Fig. 3.

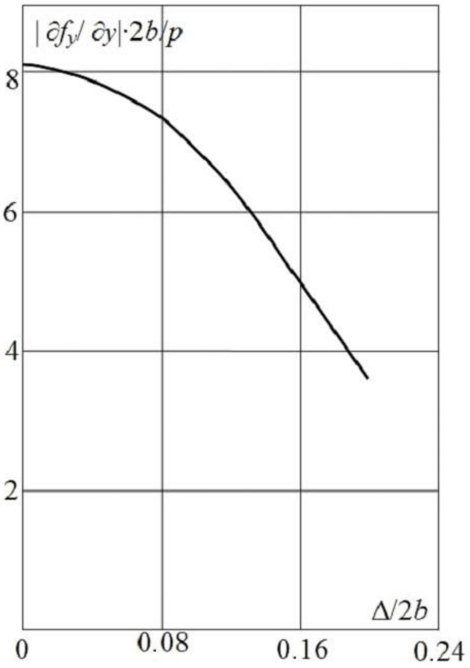

Fig. 3
Dependence of the restoring force on lateral displacement

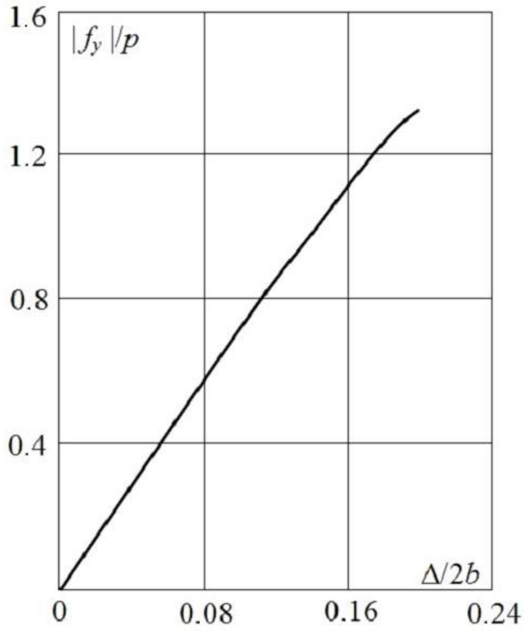

Fig. 4
Dependence of the lateral rigidity on Δ displacement

As it is seen from this chart, the suspension system with *a longitudinal joint in the guideway has lateral stability* (component f_y has property of restoring force).

It's about static stability. With small displacements, the dependence f_y on Δ is close to linear; with increasing displacement the restoring force increases slightly slower than the linear function. Along the *ordinate* axis in Fig. 3 the ratio of lateral force to the vehicle weight per one magnet – P is set; this weight is considered equal to the lifting force with zero displacement. The curve in Fig. 4 represents the dependence of lateral rigidity on the displacement Δ. The highest lateral rigidity is when the displacement is zero.

This rigidity is not much greater than 0.08 of the vehicle weight with displacement by one hundredth of the magnet width.

The curves in Fig. 3, 4 have been obtained from the calculations using the above-given formulas, corresponding to the case of infinitely wide guideway. Since in this calculation model the edge destabilising effect did not manifest itself, so we have reasonable grounds to suppose that the edge effect will decrease the value of the restoring force and lateral rigidity. Notwithstanding, EDS with a longitudinal joint will retain stability in lateral direction.

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Comparison of the suggested method of lateral stabilisation with other methods leads to the conclusion that any of the known methods of stabilisation leads to:

1) sophistication of the suspension design;
2) deterioration of other levitation characteristics of EDS.

The stabilisation method considered is not an exception. From the viewpoint of suspension design sophistication, the stabilisation with the help of longitudinal joint has a pronounced advantage over other methods, because the vehicle part of the system does not change at all, the consumption of materials per a unit of track length is the same, and sophistication of the guideway is minimal.

CONCLUSION

The expressions (5 and 6-7) completely solve the set aim of determination lateral stabilisation characteristics for EDS vehicle having a longitudinal joint in the guideway with the accepted assumptions.

Comparison with the majority stabilisation methods does not help in identification of decisive advantages or disadvantages of the new method. In most cases, its serious disadvantage is low levitation quality. This disadvantage to great extent loses its meaning, if the movement of HGTS vehicle takes place largely at high speed, in which the force aerodynamic resistance prevails over electrodynamic braking force.

The above-mentioned advantage of the considered system (high lateral rigidity) is condition-bound as well. The reason for that is that lateral rigidity requirements can be quantitatively formulated only as applied to a certain track of HGTS, considering its schedule and other factors. As it is known, the main destabilising impacts in the lateral direction are the force of inertia and lateral wind. The intensity of the former is dependent on the curve of the track and train speed, the latter - whether the train travels in the tunnel, deepening, at ground level or on an elevated track, vehicle shell form, and weather requirements.

The tasks of other HGTS' subsystems can also play their role in choosing the stabilisation system. The principle of operation and design of the traction system also plays its role. So, if the traction is carried out by means of LSM with vertical windings, the most attractive is the method of stabilisation by means of CSSGT (combined system of stabilisation, guideway, traction) [16]. At the same time, the vertical arrangement of the propulsion electromagnets imposes certain restrictions on the design of the vehicle and eliminates the possibility of using LSM to create an additional lifting force, and the latter could, in particular, mitigate the disadvantages of the method of stabilisation by means of a joint in terms of lifting force and levitation quality.

It is clear from what has been said, that the final choice of the lateral stabilisation system at the current stage of the researches would be premature.

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The new stabilisation method suggested and studied in this paper should be considered only as another possible together with the earlier proposed one. The answer to the question about the competitiveness of the new method should be related to the characteristics of the particular high-speed ground transport line. Further specification of the results is required considering the edge effect, as well the uninsulated joint case.

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