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Evaluation of stability of high-speed rolling stock on viaducts under increased peak wind load[1]

Alexander A. Vorobyev[1]✉, Yan S. Vatulin[2], Edward Yu. Chistyakov[3]

[1, 2, 3] Emperor Alexander I St. Petersburg State Transport University (PGUPS); Saint Petersburg, Russian Federation
[1] 79219751198@yandex.ru✉
[2] yan-roos@yandex.ru
[3] chistyakov@pgups.ru

ABSTRACT The authors have performed the numerical modelling of aerodynamic loads on a high-speed train running on a viaduct and evaluated the stability of a train based on the minimum load pressure on the wheel under the combined effects of crosswind and inertial air pressure (known as drift). The distribution of air pressure on the surface of train body elements in areas of overpressure and rarefaction was mapped out. The study has identified the combinations of aerodynamic impacts under which the loads on bogie wheels may decrease to unacceptable levels and established the maximum speed limits for varying aerodynamic loads that arise on coastal railway lines under stormy weather.

KEYWORDS: aerodynamic drift; inertial air pressure; high-speed train; aerodynamics; stability; viaduct

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Научная статья

Оценка устойчивости высокоскоростного подвижного состава при движении по эстакаде с учетом повышенной пиковой ветровой нагрузки

А.А. Воробьев[1]✉, Я.С. Ватулин[2], Э.Ю. Чистяков[3]

[1, 2, 3] Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС); г. Санкт-Петербург, Россия
[1] 79219751198@yandex.ru✉
[2] yan-roos@yandex.ru
[3] chistyakov@pgups.ru

АННОТАЦИЯ Выполнено численное моделирование аэродинамической нагрузки на высокоскоростной состав при его движении на эстакадах. Оценена устойчивость подвижного состава по критерию минимального давления весовой нагрузки на колесо при воздействии явления «сноса»: одновременного действия бокового ветра и инерционного наддува воздушных масс. Построена карта распределения воздушного давления на поверхности

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корпусных элементов состава в зонах избыточного давления и зонах разряжения. Определены сочетания составляющих аэродинамического воздействия, при которых формируются условия недопустимого снижения уровня весовой нагрузки на ходовые колеса тележек. Установлены предельные значения скоростного режима движения поезда в зависимости от аэродинамической нагрузки, образующейся при штормовых условиях на прибрежных участках пути.

КЛЮЧЕВЫЕ СЛОВА: аэродинамический снос; инерционный наддув воздушных масс; высокоскоростной подвижной состав; аэродинамика; устойчивость; эстакада

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INTRODUCTION

The modern view of reliable railway traffic [1] assumes that trains are to run on viaducts at certain heights with a minimum environmental impact. But in this situation, a train is exposed to a complex combination of airflows formed by the displacement and inertial dragging of air by the moving train body, as well as lateral airflows from the open space of the water surface. The resulting aerodynamic load is significantly different from that when a train runs on a high embankment.

This high-speed traffic problem is known, for example, on lines between Marseille and Montpellier of the Méditerranée Line in France. When crossing the valley of the Rhone River (south of Avignon), the TGV Duplex passes a 55-metre high viaduct at a stated speed of 300 km/h [2]. However, strong gusts of wind, which are frequent in this area, can create a significant overturning moment.

The outcomes of the study [3] show that the structure of a disturbed airflow occurring in the immediate vicinity of a running train is dependent, to a large extent, on the configuration and position of elements of nearby structures. Therefore, the problem must be considered in a generalized three-dimensional formulation taking into account the configuration of surrounding surfaces.

The stability of rolling stock under crosswind on specific track sections under certain weather conditions is regulated by the EU Technical Specifications for Interoperability (TSI)[1] [4]. The overturning moment[2] produced by the resulting effect of the wind load leads to the unloading of the wheel set, reducing the efficiency of braking and creating the risk of wheel climbing onto the top of the rail[3]. The distribution of the train weight over the wheel sets below 10 % determines the maximum permissible pressure decrease limit [5–7].

The problem is challenging to solve because the object is a multi-mass system of interacting elements with a system of elastic-dissipative connections represented by couplings between carriages [6–8].

MATHEMATICAL MODEL

The numerical modelling[4] of the aerodynamic interaction between a running train and artificial structures uses the finite volume method with solving the Navier – Stokes equations in the vector form. For incompressible viscous Newtonian fluids, these are presented as follows

$$\rho\left(\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}\nabla\right)\vec{V}\right)=\mu\Delta\vec{V}-\nabla P+\vec{f},$$

where ρ is the density of the fluid; $\vec{V}$ is the speed of the fluid; μ is the kinematic viscosity; P is the pressure; and $\vec{f}$ is the vector of mass forces, which, in addition to gravity, may be of various nature (electrical, magnetic, etc.).

The mathematical modelling of the loss of stability of a train included constructing and solving differential equations [7] that describe forced oscillations of a dual-

[2] Technical Specifications for Interoperability (TSIs). European Union Agency for Railways. URL: https://www.era.europa.eu/domains/technical-specifications-interoperability_en

[3] TS 002/2011. Technical Regulation “On Safety of High-Speed Railway Transport” (adopted by Decision of the Commission of the Customs Union No. 710 dated July 15, 2011 (as amended on March 30, 2023) “On Adoption of Technical Regulations of the Customs Union “On Safety of Railway Rolling Stock”, “On Safety of High-Speed Railway Transport”, and “On Safety of Railway Infrastructure”. URL: http://docs.cntd.ru/document/902293437

[4] Studies on the topic were performed as part of the implementation of the Priority 2030 Federal Program for University Support.

mass system impacted by external force factors from harmonic disturbances with a displacement limit for the projection of the centre of mass of a carriage under the influence of a system of disturbing aerodynamic lift and crosswind forces [8].

To evaluate the force impact of moving airflows on a train, it is necessary to identify mechanisms of transmitting external aerodynamic loads from the train body surface to the bogie and further to the track superstructure. To this end, we need to take the following steps:

- make a computational model for determining aerodynamic pressure on the body of a moving train by the finite volume method using approaches of the elasticity theory;
- identify the formation mechanism of aerodynamic drag for a Sapsan high-speed train running on a viaduct of a certain height in crosswind conditions;
- determine the dynamic response of the elastic-yielding suspension of a train to disturbances from the aerodynamic impact;
- determine the forces in wheel–top-of-rail contacts at different train speeds and crosswind speeds.

Input

To model the lateral air flows, the conditions for the formation of aerodynamic loads under a strong storm and hurricane (according to the Beaufort scale) are taken as follows: 12 m/s — 6 points; 27 m/s — 10 points; 36 m/s — 12 points. A high-speed electric train on the Siemens Velaro platform, in particular, Velaro RUS (EVS2 Sapsan), is used for computation purposes. The main characteristics of the train are as follows: number of carriages: 10; number of carriage axles: 4; carriage length: 24.73 m; train length: 246.27 m; train weight: 6,412 kN; average axle load: 26.04 kN/m; carriage height above top of rail: 5 m. The adopted top of rail level above the ground corresponds to the 4.0 m mark. The characteristics of the shock absorber of the automatic coupling device are as follows: spring stiffness: 26.21 MN/m; damping coefficient: 35 N·s/mm.

The Sapsan has a two-level suspension system. The primary spring suspension (wheel–bogie) is implemented by single-link axle boxes, hydraulic vertical shock absorbers, and cylindrical coil springs — 1400 kN/m. The secondary spring suspension (wheel–bogie) is implemented using pneumatic cylinders, hydraulic vertical and lateral shock and wobble absorbers — 670 kN/m. Besides, the train undercarriage assembly is provided with a lateral stability (anti-sway control) system: primary: 1,100 kN/m, secondary: 410 kN/m.

The dimensional properties of the viaduct superstructure and abutment are given in *Fig. 1*.

MODELLING OF AERODYNAMIC LOADING

The aerodynamic impact on elements of the train body forms a three-dimensional resultant vector of air movement relative to the train (*Fig. 2*): in the horizontal plane (the wobble angle) and in the vertical plane (the pitch angle).

For a constant train speed and the assumed stable crosswind model [9], the total vector of the aerodynamic impact on the train body is determined using the following formula

$$V_s = \sqrt{V_t^2 + V_r^2},$$

where V_t is the vehicle speed, m/s; V_r is the crosswind airflow speed, m/s. The wobble angle is: $\tan a = V_r/V_t$.

The steady-state aerodynamic forces F and moments M are determined as follows

$$F = 0.5\rho S C_F(a) V_r^2;$$
$$M = 0.5\rho S h C_M(a) V_r^2,$$

where C_F is the aerodynamic force coefficient; C_M is the aerodynamic moment coefficient; ρ is the air density, kg/m³; S is the control area, m²; and h is the control height, m.

The modelling of a gusty crosswind is performed using the method set out in the Code of Practice SP 20.13330.2011[5], Section 11 “Wind Impacts”. The line is located in two wind speed zones 4 and 5 and two wind pressure zones I and II, corresponding to 30.59 kg/m² (section 11.1.4, Table 1.1, Annex G). The standard value of the average wind load component per 1 m² of the windward surface of the train is

$$W_m = W_o K_1 C_x = 48.09 \text{ kg/m}^2,$$

where W_o = 30.59 is the standard wind pressure for zone II (section 11.1.4); K_1 = 1.31 is the coefficient to account for the change in wind pressure based on terrain height A (section 11.15); and C_x = 0.2 is the aerodynamic coefficient [10].

The standard value of the wind load pulsation component at the height z should be determined as follows (section 11.1.8)

$$W_p = W_m K_s N_u = 19.33 \text{ kg/m}^2,$$

where K_s = 0.67 is the wind pressure pulsation coefficient for level Z (section 11.1.8); and N_u = 0.6 is the coefficient of wind pressure pulsation spatial correlation coefficient (section 11.1.11).

[5] SP 20.13330.2011. Loads and impacts. Updated version of SNiP 2.01.07-85*. URL: https://docs.cntd.ru/document/1200084848

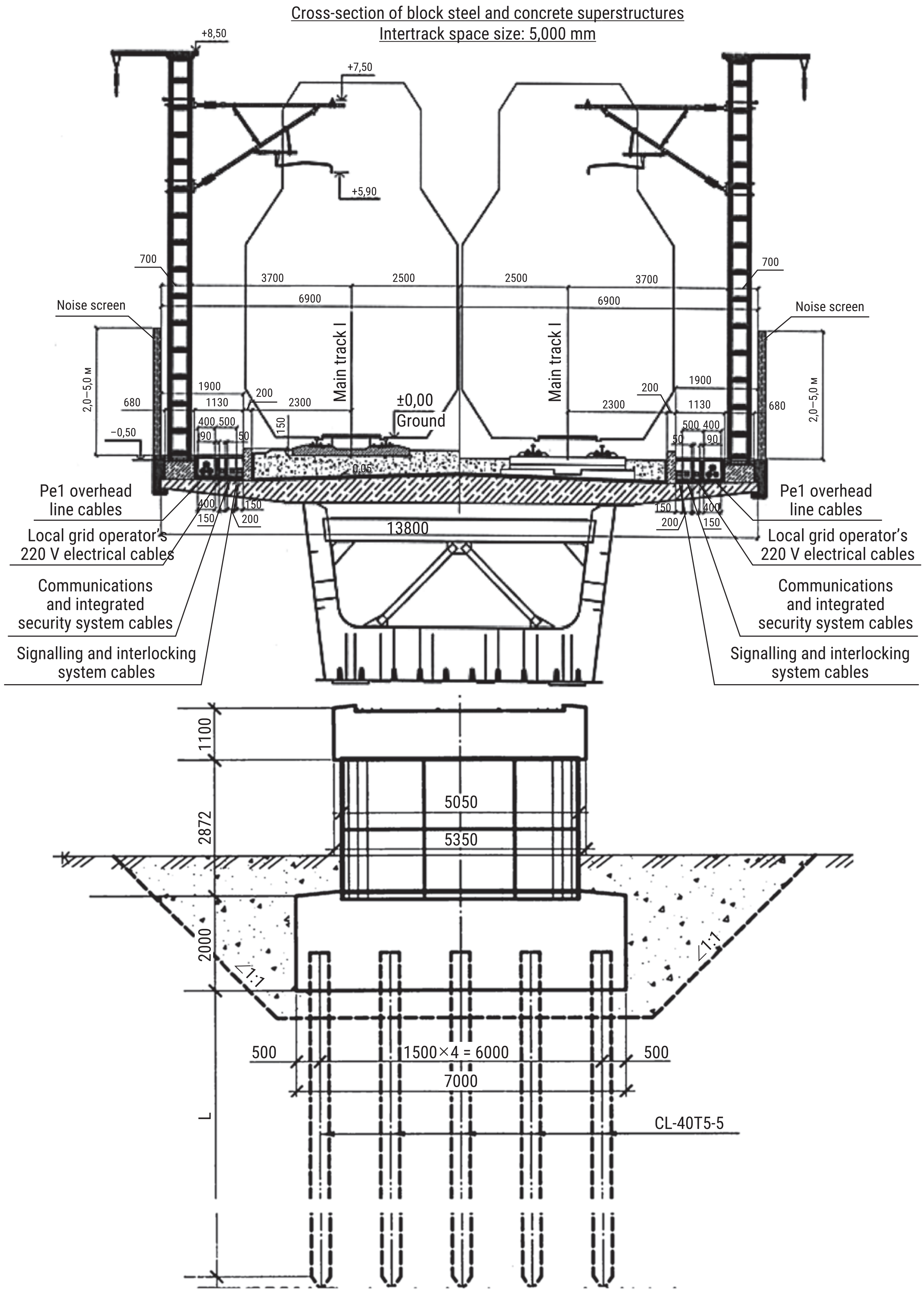


Fig. 1. Dimensional properties of the viaduct superstructure and abutment

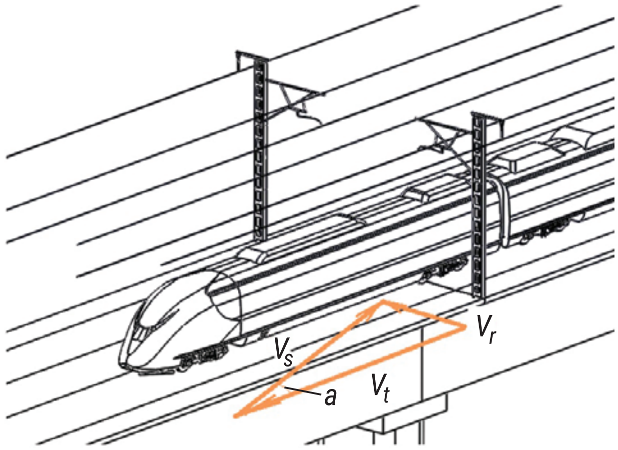


Fig. 2. Movement of air masses relative to the train

The positive peak wind load (section 11.2) is as follows

$$W_z = S(W_m + W_p) = 67.42 \text{ kg/m}^2 \text{ (0.66 kPa)};$$
$$S = 1 \text{ is the area, m}^2.$$

In the adopted *k*–ε turbulence model, the base mesh size is 0.4 m, condensing down to 0.01 m in areas closer to the train walls and the surfaces of peripheral structures. At the same time, the wall boundary layer is fully within the first grid layer from the wall.

The model is based on the following assumptions:

- in order to reduce the dimensionality of the problem, a number of structural components that have no material influence on aerodynamic properties of the object were excluded from the models;
- the non-stationary movement of circulating flows is taken into account by applying the air friction coefficient and is determined as the tangential friction force per unit of surface area of the interface between the liquid layers;
- the temperature is constant throughout the computational domain;
- the effects of convection processes and gravity are negligible;
- the carriage body, bogies and track components are assumed as absolutely solid bodies relative to the rigidity of the springs;
- the wheel sets are constantly in contact with rails;
- the spring suspension is assumed to be inertia-free due to low masses.

RESULTS OF NUMERICAL MODELLING OF AERODYNAMIC PROCESSES

The results of the numerical modelling of volumetric displacement of directionally moving air by a solid object have been competently confirmed by an experiment carried out on scale models by the Scientific and Technical Centre for Construction (Centre Scientifique et Technique du Batiment (CSTB)).

However, there are certain differences. The experiment used a stable object located at the ground level. The wind shadow created by the train body and viaduct has a particular configuration due to the free space under a viaduct superstructure. In particular, on the windward side, the airflow is divided into two parts. The upper part passes over the roof and side surfaces of the body, where high-speed zones prevail, promoting the formation of a negative pressure zone. The second part goes towards the free space under the viaduct superstructure (*Fig. 3*). The lower part of the carriage body side surface and the undercarriage space are in the zone where the divided air flows sharply change direction, causing the speed to decrease and the environmental pressure to rise. When, for instance, the train moves on a high embankment, its undercarriage area is exposed to a strong impact from the air masses that move at a growing rate.

The averaged values of air pressure on the surface of the head carriage body on the windward and leeward sides are given in *Table 1*.

The total flow of air passing over the carriage body creates a characteristic structure of complex-shaped stall vortices on its surface as shown in *Fig. 4* by the air movement vectors.

It should be noted that there is a consistent tendency of displacement (drift) of crosswind vortex generation areas in the direction of travel on the curved part of the roof surface with an increase in the train speed and growth of the process intensity with an increase in the crosswind speed.

The study of the distribution of air pressure along a high-speed train shows that at varying train and crosswind speeds, the situation remains the same as long as the speed does not exceed 300 km/h. However, as the speed increases, significant pressure fluctuations occur

Table 1

Air pressure on the side surface of the head carriage body on the windward and leeward sides

Train speed, km/h	Load side, Pa	Crosswind speed, m/s		
		12	27	36
200	Windward	−6.2	35.1	62.7
200	Leeward	−128	−387	−653.6
300	Windward	−26.9	110.9	123.5
300	Leeward	−191.2	−403.1	−650.5
400	Windward	−103.1	138.5	248.1
400	Leeward	−319.7	−424	−669.1

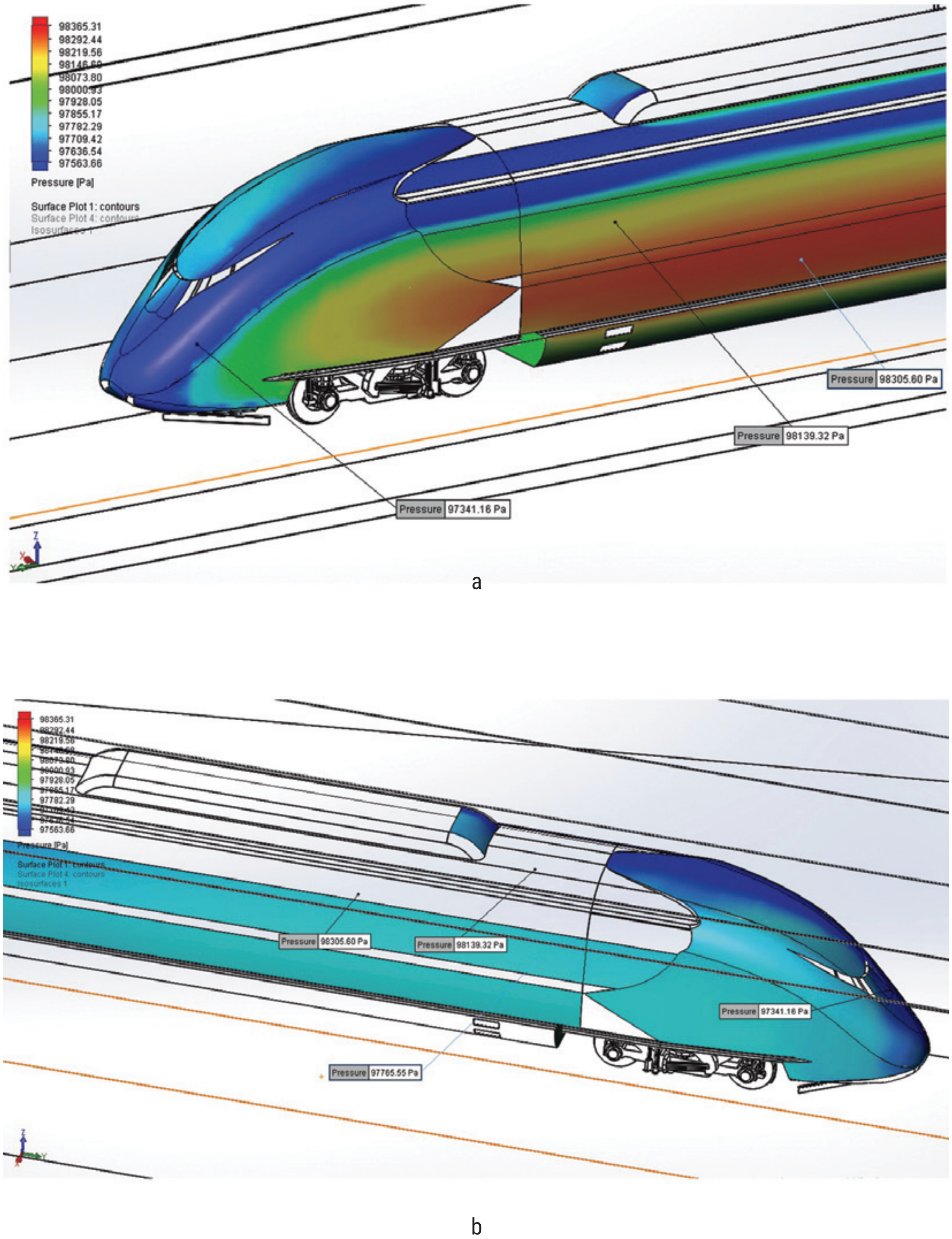


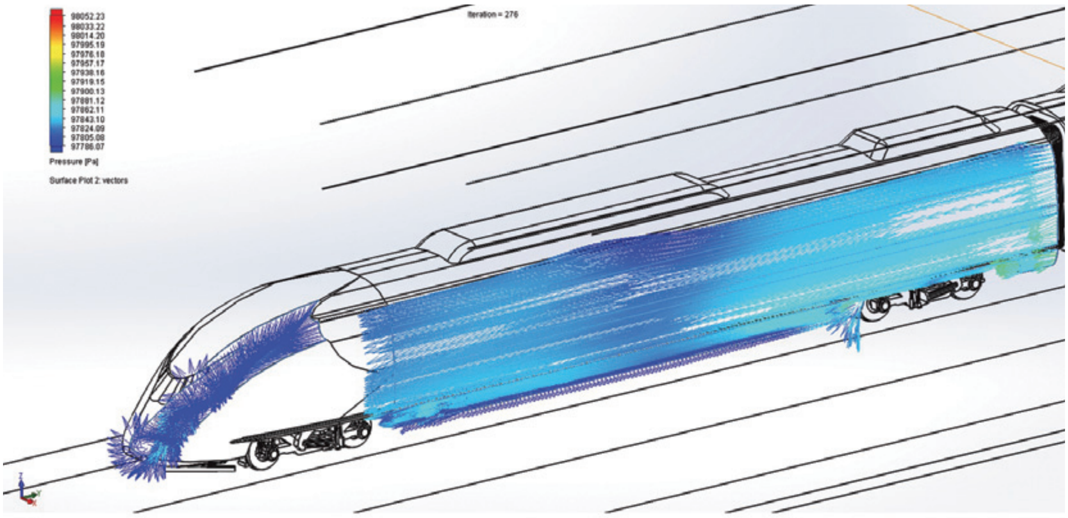
Fig. 3. Air-load distribution on the surface of the head carriage body (train speed: 300 km/h; crosswind speed: 23 m/s): *a* — windward surface; *b* — leeward surface

on the windward side of the carriage body, especially in the area of few first carriages of the train.

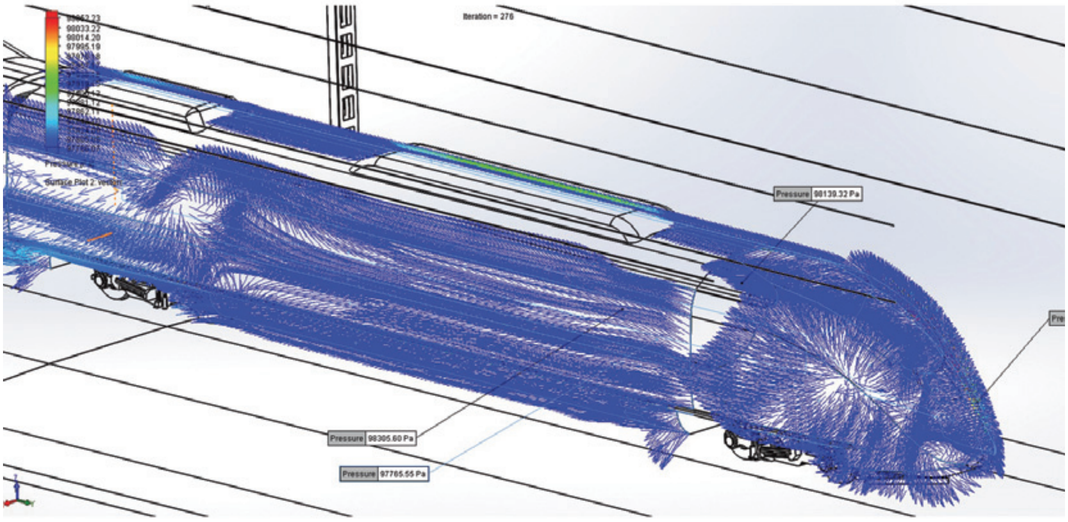
It follows from *Table 1* that the end carriages of the train are exposed to the maximum impact from the disturbed airflow (the closer to the rear carriage the higher the exposure) and that the force becomes higher with an increase in the speed of the train. When the crosswind speed is increased to more than 27 m/s, the number of clusters on the carriage body surface where air pressure exceeds the established maximum permissible pressures from the wind load of 0,5 kPa grows in multiples[6].

The resulting difference in pressures from the disturbed air on the windward and leeward surfaces of

[6] NUCARS. Transportation Technology Center Inc Pueblo. Colorado USA, 2017. URL: http://www.aar.com/nucars/



a



b

Fig. 4. Inertial drift of the total flow of air along the carriage body surface: *a* — prevailing crosswind at a train speed of up to 200–300 km/h; *b* — drift of the epicentre of stalled airflows towards the rear carriage at a train speed of above 300 km/h and a crosswind speed of 32 m/s

the carriage body causes a dangerous sideways movement, contributing to the loss of stability and increasing the risk of derailment.

MODELLING A DUAL-MASS DYNAMIC SYSTEM EXPOSED TO EXTERNAL FORCE FACTORS OF HARMONIC DISTURBANCE

The undercarriage suspension system of a train can be represented as a two-level system of upper and lower vertically installed oscillators which, respectively, determine the rigidity of the primary and secondary suspension *1*, and horizontally located oscillators *2*, which determine the lateral rigidity of the suspension (*Fig. 5*).

The ratio of the stability moment to the overturning moment6 within the range of n = 1.25 serves as the limit for stability of a carriage

$$n = \frac{QL_Q}{F_{H2}L_{H2} + F_{H1}L_{H1} + F_{V1}L_{F_{V1}} + F_{V2}L_{F_{V2}}} > 1.25.$$

The model is based on the following assumptions:

- in order to reduce the dimensionality of the problem, a number of structural components that have no material influence on dynamic properties of the object were excluded from the models;
- the carriage body, bogies and track components are assumed as absolutely solid bodies relative to the rigidity of the springs;
- the spring suspension is assumed to be inertia-free due to low masses;

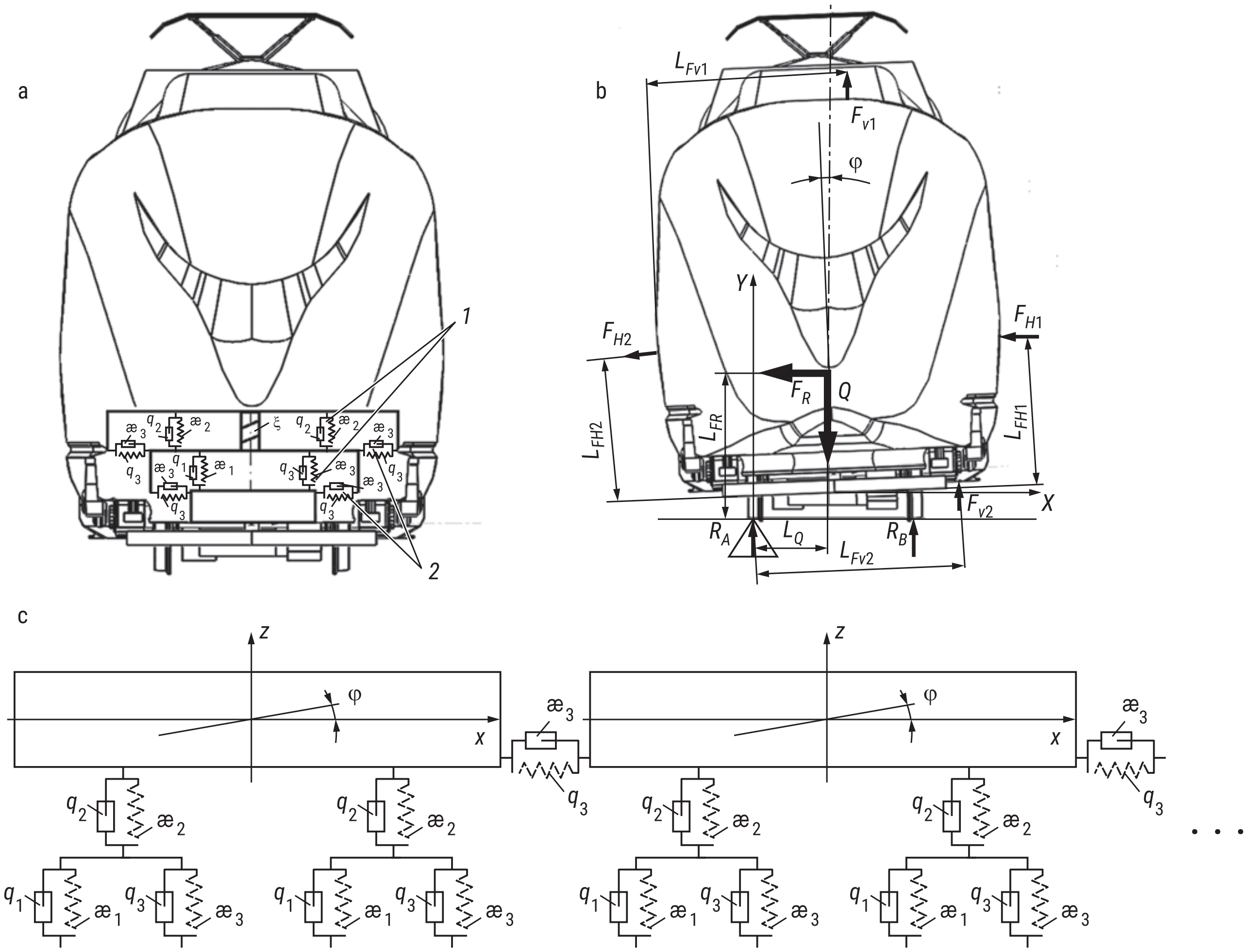


Fig. 5. Scheme for determining crosswind stability of a train: *a* — modelling an undercarriage suspension assembly of a train carriage; *b* — carriage body loading scheme; *c* — scheme of elastic-damping connections in a multi-mass system; *Q* — gravity; L_{FR} — distance to the centre of gravity; F_R — wind force; F_{V1} — aerodynamic lift on the roof (clusters 1 and 2 (according to *Table 2*)); F_{V2} — aerodynamic lift on the bottom (cluster 3 (according to *Table 2*)); F_{H1}, F_{H2} — lateral forces (F_{V2} — clusters 4 and 5); $L_{F_{V1}}$, $L_{F_{V2}}$ — distance to the aerodynamic centre on the roof and on the bottom; $L_{F_{H1}}$, $L_{F_{H2}}$ — distances to the centre of crosswind forces; L_Q — distance to the point of application of gravity

- the oscillating system is assumed as a dual-mass (body–bogie) system, with wheel sets being constantly in contact with rails, and the rim flanges on one side of the wheel sets being pressed to the top of the rail when in motion;
- the model is based on free oscillation from external forces of the disturbance caused by a peak gust load.

The carriage body is exposed to a single positive peak wind load.

RESULTS OF NUMERICAL MODELLING OF TRAIN DYNAMICS UNDER A SINGLE POSITIVE PEAK WIND LOAD ON THE SIDE SURFACE

The study has established that at a train speed of 200 km/s and a crosswind velocity of 12 m/s, the structure has the maximum range of angular deviation

Table 2

Loads on bogie wheels at airflow rates of 12 m/s and 36 m/s (wheel load distribution percentage)

Rail	Loads on front bogie wheels, kN		Loads on rear bogie wheels, kN	
At an airflow rate of 12 m/s				
Right	7.26 (11.6)	8.03 (12.8)	7.65 (12.24)	8.33 (13.32)
Left	7.41 (11.8)	7.68 (12.28)	7.9 (12.64)	8.28 (13.24)
At an airflow rate of 36 m/s				
Right	10.57 (14.4)	10.58 (14.4)	8.08 (11)	12.3 (16.75)
Left	7.27 (9.9)	7.97 (10.85)	8.13 (11)	8.5 (11.5)

of 0.076 degrees and returns to a steady state within 1.8 seconds. At a crosswind velocity of 36 m/s, the range of angular deviation increases to 0.235 degrees and the steady state returns within 2 seconds. The respective loads on bogie wheels at airflow rates of 12 m/s and 36 m/s are given in *Table 2*.

These figures show that at an airflow rate of 12 m/s, the minimum load on a bogie wheel does not exceed the permissible limit of 10 % of the rated load, while at an airflow rate of 36 m/s, the minimum load on the bogie wheel exceeds the permissible limit of 10 % of the rated load on the left wheel of the front bogie.

CONCLUSIONS

We have proposed the mathematical models and performed the numerical modelling of the multi-factor process of aerodynamic impacts on a high-speed train running on a viaduct in a coastal area during a ten-point storm (on the Beaufort). The outcomes showing the patterns of distribution of airflows near a moving train have enabled us to determine the values of pressure on its surfaces caused by inertial air pressure and the dragging of air by the moving train.

We have found that the drift of the stalled airflow towards rear carriages promotes a significant difference in pressures between the windward and leeward surfaces of the carriage body. This causes dangerous sideways movement in a portion of the train as a result of mutual impacts of elastic-yielding couplings between carriages and impedes the oscillatory process in wheel–rail contacts accompanied by a decrease in the contact pressure on the wheel–rail interface.

The study has found that at a train speed of 200 km/h, an increase in crosswind velocity from 12 to 36 m/s causes a 32 % increase in the angular deviation of a carriage and a 10 % increase in the time required for the stabilization of the sprung mass. At the same time, the load on the left wheel of the front bogie is below the permissible minimum of 10 % of the rated weight load, which increases the risk of losing the adhesion between the wheel and the rail and hence reduces the braking efficiency at a given speed. It has been shown that for train speeds of up to 300 km/h, the allowable crosswind gust speed should not exceed 27 m/s.

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Bionotes

Alexander A. Vorobyev — Dr. Sci. (Eng.), Associate Professor, Professor of the Department of “Ground Transport and Technological Complexes”; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; SPIN-code: 2244-1699, ID RSCI: 290846, ORCID: 0000-0002-0534-5687; nttk@pgups.ru;

Yan S. Vatulin — Cand. Sci. (Eng.), Associate Professor; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; nttk@pgups.ru;

Eduard Yu. Chistyakov — head of Quality, Licensing and Accreditation Department, Senior Lecturer of the Department of Construction Materials and Technologies; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; chistyakov@pgups.ru.

Об авторах

Александр Алфеевич Воробьев — доктор технических наук, доцент, профессор кафедры «Наземные транспортно-технологические комплексы»; **Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС)**; 190031, г. Санкт-Петербург, Московский пр., д. 9; SPIN-код: 2244-1699, РИНЦ ID: 290846, ORCID: 0000-0002-0534-5687; nttk@pgups.ru;

Ян Семенович Ватулин — кандидат технических наук, доцент; **Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС)**; 190031, г. Санкт-Петербург, Московский пр., д. 9; nttk@pgups.ru.ru;

Эдуард Юрьевич Чистяков — начальник Управления качеством, лицензирования и аккредитации, старший преподаватель кафедры «Строительные материалы и технологии»; **Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС)**; 190031, г. Санкт-Петербург, Московский пр., д. 9; chistyakov@pgups.ru.

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Corresponding author: Alexander A. Vorobyev, 79219751198@yandex.ru.
Автор, ответственный за переписку: Александр Алфеевич Воробьев, 79219751198@yandex.ru.

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