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Development of a Numerical Model of the Aerodynamic Interaction of a High-Speed Train, Air Environment and Infrastructure Facilities

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ABSTRACT

The design of high-speed railway lines (HSR) requires mandatory consideration of loads from the aerodynamic interaction of a moving train, the air environment and infrastructure facilities, acting both on structures and facilities, and on the train itself. Software systems of computational fluid dynamics are most expedient to determine the nature and intensity of the load.

To find the optimal approach to modelling the processes of aerodynamic interaction between a moving high-speed train and the air environment, as well as to assess the degree of validity of the simulation, a series of calculations were performed in the ANSYS CFX software environment using various approaches to the construction of calculation models (the sliding grid method and the immersed solid method). An analysis of the results of the performed calculations makes it possible to determine the area of rational application of the considered approaches in the development of computational models of aerodynamic interaction.

To verify the developed calculation models, experimental measurements of the aerodynamic impact of Sapsan high-speed electric train on the air environment were performed. Also, the developed models were verified based on the results of similar international experimental studies. Comparison of the results of numerical simulation and experimental measurements allows us to conclude that the developed computational models are sufficiently valid and can be further applied.

Keywords: rail transport, high-speed railways, high-speed train, aerodynamics, aerodynamic interaction, numerical modelling, simulation.

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INTRODUCTION

High-speed rail (HSR) places extremely high demands on reliability, durability and safety of all components of the infrastructure. Some of these requirements are determined by the need to consider when designing a number of special loads and impacts, the consideration of which is not mandatory when designing conventional (not high-speed) railways. One of these loads is the load from the aerodynamic interaction of a moving high-speed train, the air environment and infrastructure [1; 2]. Of particular importance is the study of the aerodynamic impact exerted by high-speed rolling stock on infrastructure facilities, people, other rolling stock, etc. in the context of design of the St. Petersburg–Moscow high-speed rail (HSR-1) with an operating speed of up to 360 km/h.

RESULTS

Aerodynamic Interaction of a Moving High-Speed Train, Air Environment and Infrastructure Facilities

The movement of a high-speed train is accompanied by local perturbations of the air environment that cause formation of zones of increased (excessive) and reduced (rarefied) pressure along the train. The formation of these zones is caused by compaction and decompression of air masses in the immediate vicinity of the moving train. A sharp change in areas of high and low pressure forms an alternating travelling air wave moving at a speed equal to the speed of the train. The most pronounced air waves are located at the head and end of trains. Also, similar waves, but with lower amplitudes of pressure values, are located at the inter-car gaps and at the places of coupling of articulated trains [3–5]. The principal graph of pressure change along a single high-speed electric train is shown in Pic. 1.

Moving air waves flow around structures and facilities located in the vicinity of the axis of the track, which leads to different pressure values along their contour at a time. The resulting pressure difference forms the total aerodynamic force and the total aerodynamic moment acting on the body under consideration [6]. At the same time, when air waves are flowing around various types of structures, there is a possibility of local eddies that can affect the dynamic operation of the structure under consideration and wind stability of a moving train.

As a rule, the most reliable way to study various aerodynamic phenomena is physical modelling in wind tunnels and installations (Pic. 2).

However, since physical modelling is extremely labour-intensive, and some of the problems under study (for example, modelling flows around static bodies caused by a moving body) are unrealisable in wind tunnels [7], and their modelling using specialised installations is rather laborious, it is necessary to resort to numerical simulation methods. in specialised software systems intended for computational fluid dynamics (CFD).

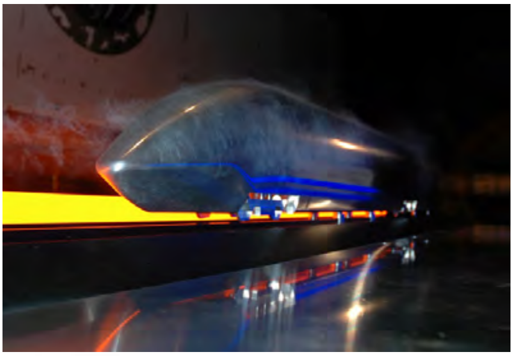
Design Model Development

Numerical simulation in software systems is a relatively young method for studying aerodynamics, which has become widespread thanks to a significant increase in computing power. The numerical simulation method is based on solving a system of air medium continuity equations, equations of motion and energy conservation, supplemented by equations of air flow turbulence models.

To solve the system of equations, software systems use the finite volume method, which consists in dividing the computational domain

Pic. 1. Principal graph of the change in the magnitude of air pressure along a high-speed train [developed by the author].

a)



b)

Pic. 2. Tests of train models in wind tunnels: a – electric train built on the Siemens Velaro platform, b – electric train built on the Alstom AGV platform [https://www.dlr.de/next/desktopdefault.aspx/tabid-6710/11006_read-25184/, https://www.techinsider.ru/technologies/10632-protiv-vetra-aerodinamika].

into non-intersecting control volumes (Pic. 3) [8–9].

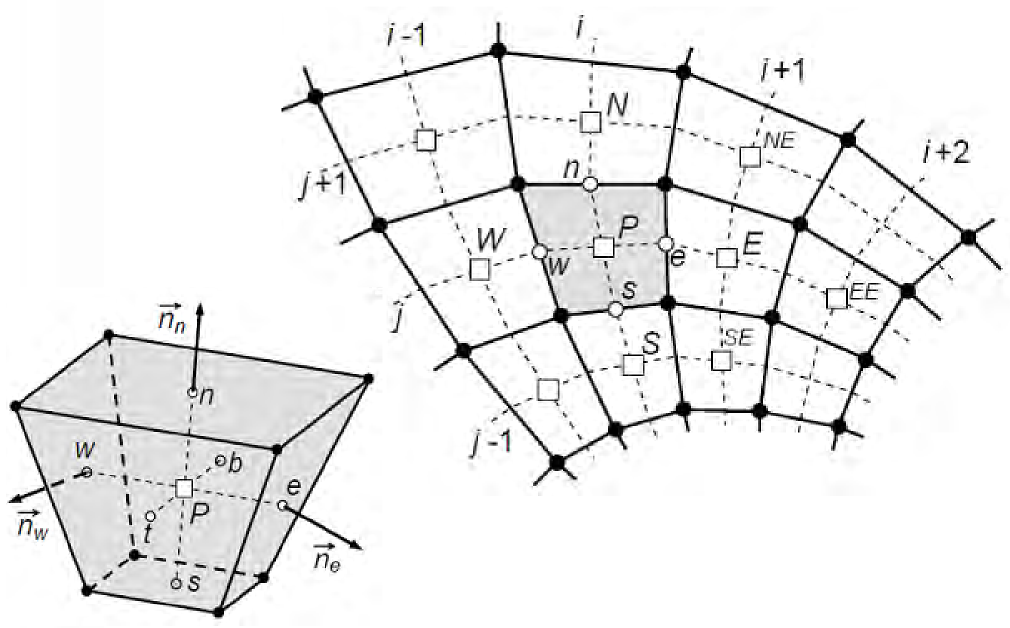
The procedure for solving CFD problems can be divided into three main stages: the preparatory stage, the main stage, and the post-processing stage. At the preparatory stage, a three-dimensional geometric model of the problem under consideration is developed with its subsequent discretisation (building a computational grid). At the main stage, the parameters of the computational experiment are set (turbulence model, boundary and initial conditions, time discretisation) followed by computation.

The post-processing stage is devoted to construction of distribution patterns, graphs of pressures, velocities, kinetic energy and other required characteristics of the air environment.

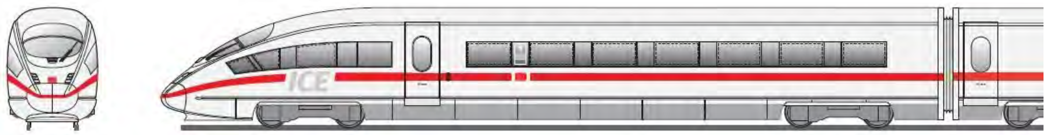
The ANSYS CFX software package was chosen as the software that allows to perform a full range of works on numerical modelling of the aerodynamic interaction of a high-speed train, the air environment and infrastructure facilities, as well as aerodynamic calculations both in stationary and non-stationary settings.

Development of a Geometric Model of a High Speed Train

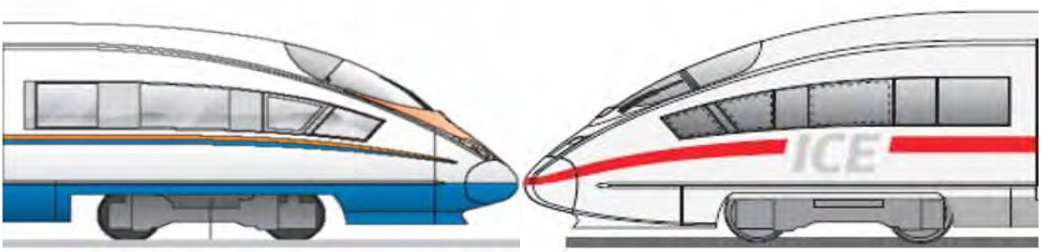
High-speed electric trains based on the Siemens Velaro platform were accepted as the



Pic. 3. Grid of control volumes with reference to the centre of the cells [9] (□ is the centre of the volume, ● is the grid node, ○ is the middle of the face).



Pic. 4. High-speed electric train based on the Siemens Velaro platform [https://german160.wordpress.com/author/mytrainmaster/page/7/].



a) *b)*

Pic. 5. Head fairing shape of a high-speed train: a – ICE3, b – EVS1/2 «Sapsan» [https://german160.wordpress.com/author/mytrainmaster/page/7/, http://emupages.ru/history-technology-highspeed-sapsan.htm; refined by the author].

calculated rolling stock. To date, trains built on this platform are operated on speed and high-speed railways in Germany (ICE-3), Spain (AVE S-103), China (CRH 3) and Russia (EVS 1, EVS 2).

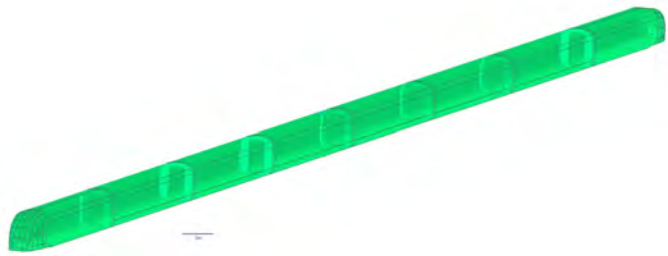
One of the fundamental factors for choosing the calculated train was the operation of the high-speed train EVS 1/2 Sapsan on the existing network of Russian Railways. A significant difference between the Sapsan and other single-platform trains is the change in the shape of the head fairing (Pic. 5), due to Russian requirements for the rolling stock in operation.

The composition of the calculated train is assumed to be assembled according to the eight-car scheme (two head and six intermediate cars).

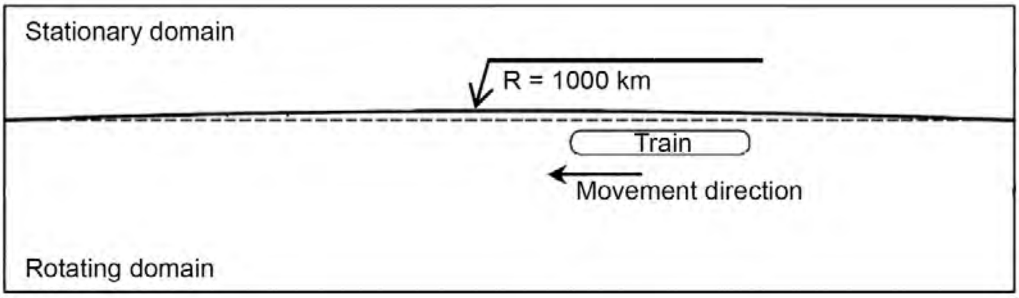
The development of a three-dimensional geometric model of a high-speed train was carried out in AutoCAD environment with subsequent refinement and preparation with the SpaceClaim software. To optimise the computational grid and reduce the computation time, several simplifications were made in the geometric model, which have a local effect and do not significantly affect the distribution of air masses around the train cars. The developed geometric model is shown in Pic. 6.

Development of a Model Based on the Sliding Grid Method

When solving the problem of aerodynamic interaction of a moving high-speed train, the air environment and infrastructure facilities, the most convenient and correct modelling method is to use the sliding mesh (grid) method [10–12]. When using this method, the calculation model is divided into stationary and non-stationary components. The non-stationary component is the volume of air, from which the volume equivalent to the train model is subtracted, with a given direction and speed of movement. The stationary component is a fragment of the air environment with the considered infrastructure objects located in it, in which a «tunnel» is cut out for movement of the non-stationary component of the model in it. The



Pic. 6. The developed geometric model of the Sapsan high-speed electric train [developed by the author].



Pic. 7. Schematic diagram of the model based on the «rotor–stator» model [developed by the author].

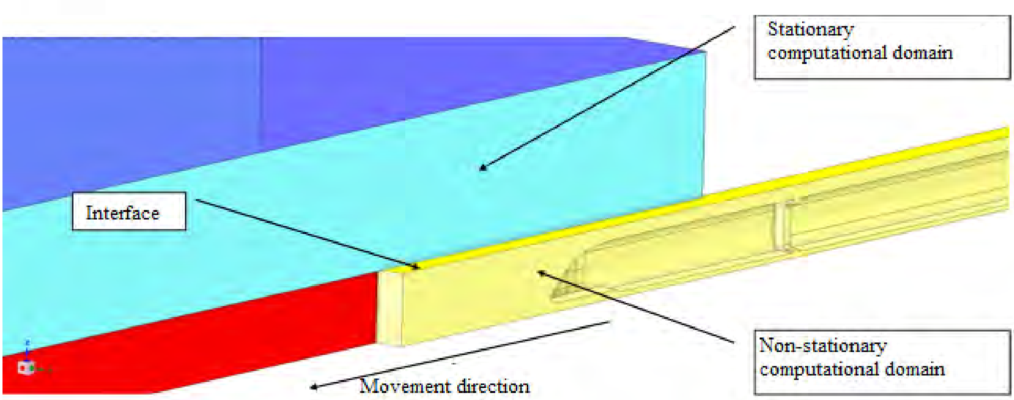
interaction of the stationary and non-stationary parts of the model is carried out through the grid interface. The most accurate operation of the grid interface is achieved with rotational relative motion of the computational domains (rotor–stator model). Thus, when specifying movement of the non-stationary part of the calculation model along a circle of large radius (more than 1000 km), its linear movement can be simulated (Pic. 7).

This approach requires an extremely precise development of the geometry of the computational domain due to the curvature of the surfaces of the contact interfaces. Also, to determine the aerodynamic force and moment acting on the train, it is necessary to set an individual dynamic coordinate system for each car of the calculated train. Considering the above factors, it was decided to resort to setting the movement of the non-stationary part of the model not as of rotational movement along an infinitely large radius, but as of translational motion while setting it through commands in the CFX CCL command language. The schematic diagram of the developed calculation model is shown in Pic. 8.

The main advantage of using this method is the possibility of working out the boundary layer both around the structures and facilities under consideration, and directly around the train. Setting the near-wall layers close to the cars allows getting the correct pressure gradient on the walls of the cars and, as a result, the magnitude of the force and moment acting on them, which makes it possible to most correctly solve the problems of aerodynamic stability of a high-speed train moving over bridges (or embankments) under side wind and the problems of interaction of the train and superstructures when the train drives below (for example, through lattice truss bridges).

For the problem under consideration, a universal SST model, which is most often used in problems of architectural and construction aerodynamics and rolling stock aerodynamics was chosen as a turbulence model describing the disorder of the movement of air masses, since SST model demonstrates high accuracy and reliability both in near-wall flows and at distances from the walls [13−16].

When developing the model, movement of the train along the earth's surface was simulated. The accepted level of the earth's surface corresponds to the mark of the rail head (1,1 m from the level of



Pic. 8. Scheme of the calculation model based on the sliding grid method [compiled by the author].

the automatic coupler/mask of the head fairing for the Sapsan electric train). Since in the problem under consideration the values of extreme pressures of the head and tail air waves located above the level of the head fairing are decisive, simulation of the superstructure and track embankment was not performed.

For the upper and side faces of the calculated air volume, «opening» boundary conditions were set, which ensure the possibility of reverse flows on the surface. For the lower face of the air volume (earth's surface) boundary conditions «free slip wall» are set, for the surface of the train the boundary conditions «no slip wall» is assumed.

The Reynolds number for the developed models ranges from $12{,}3 \cdot 10^6$ (at a train speed of 200 km/h) to $15{,}4 \cdot 10^6$ (at a speed of 250 km/h). The number of finite volumes of the computational model was 1,2 million for the stationary region and 7,5 for the mobile region. The size of the grid elements on the surface of the train did not exceed 0,01 m. The size of the grid elements of the air array varied from 0,05 to 0,5 m with thickening in the region of the moving domain. The boundary layer near the train surfaces was not studied in detail since its setting is not decisive for the calculation of aerodynamic loads on the surrounding infrastructure.

The problem was considered in a non-stationary formulation in the range of physical time 6…10 s. The time step was 0,005 s. The Courant number C_o did not exceed 2.

Development of a Model Based on the Immersed Solid Method

The sliding grid model provides the most complete and reliable picture of the interaction of high-speed rolling stock, both in terms of the impact on the infrastructure and the impact on the rolling stock. However, the application of the sliding grid method is quite costly in terms of computational resources and time for solving the problem, since at each time step it is required to rebuild the computational grid.

At the same time, when determining the magnitude of the aerodynamic impact only on infrastructure facilities, setting and modelling the near-wall layer around a high-speed train is not mandatory. This assumption allows us to apply the immersed solid model, in which the train model, represented by a solid body, is placed in the calculated air volume with set direction and speed of movement in this volume. The principle of operation of this model is to form a calculation grid for the air area and the calculation train with their further overlap. Next, the solver at each time step determines the overlapping nodes of the air domain and sets the air speed in them to be equal to the speed of the rigid body.

The total number of elements of the calculation model is 24,1 million cells. The size of the cells of the computational domain is in the range from 0,5 m to 0,01 m (concentration towards the area of the moving body). The maximum size of a train element is 0,01 m. The Reynolds numbers and other boundary conditions of the calculated air volume and the parameters of the non-stationary setting (physical time, time step, etc.) are determined similarly to the problem using the sliding grid method. The Courant number did not exceed 3.

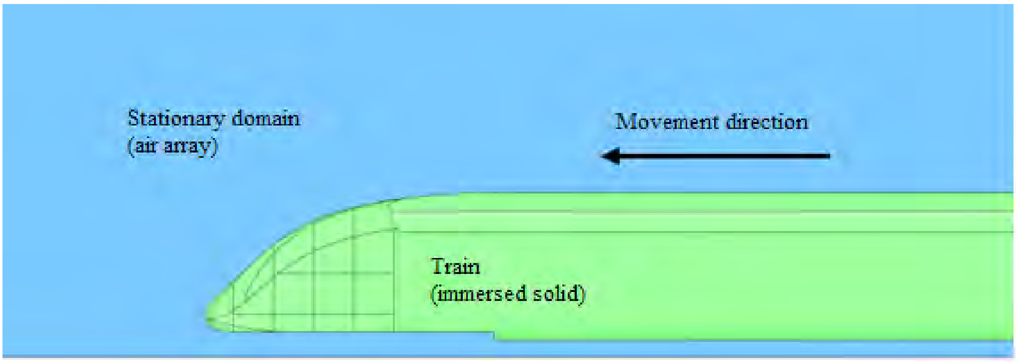
Experimental Verification of the Developed Calculation Models

To assess the validity rate of the results obtained using the developed calculation models, they were verified based on the results of experimental measurements of the aerodynamic impact on the air environment of the Sapsan high-speed electric train [17].

Experimental measurements were made on separate sections of the St. Petersburg–Moscow railway line with set speed limits from 200 to 250 km/h. The choice of measurement sites was carried out jointly with the employees of Bridge Test Station No. 1 of Oktyabrskaya Railway, preceded by an analysis of the currently set speeds and of the presence of possible places where the train had to change speed (dangerous places, stations, curves, works on the track) in the sections under consideration. Thus, the places determined for measurements were located in the areas of uniform motion. Additionally, the speed of trains was considered according to the results of the graphs of the performed measurements (according to the distance between the head and tail air waves). The deviation of the actual speed from the established one on the site was no more than 4 km/h (downward).

The measurements were carried out by high-frequency membrane overpressure sensors installed in the immediate vicinity of the track axis. The measurement process is shown in Pic. 10.

The measurement results are graphs of excess pressure changes at a fixed point during the



Pic. 9. Scheme of the calculation model based on the immersed solid method [compiled by the author].

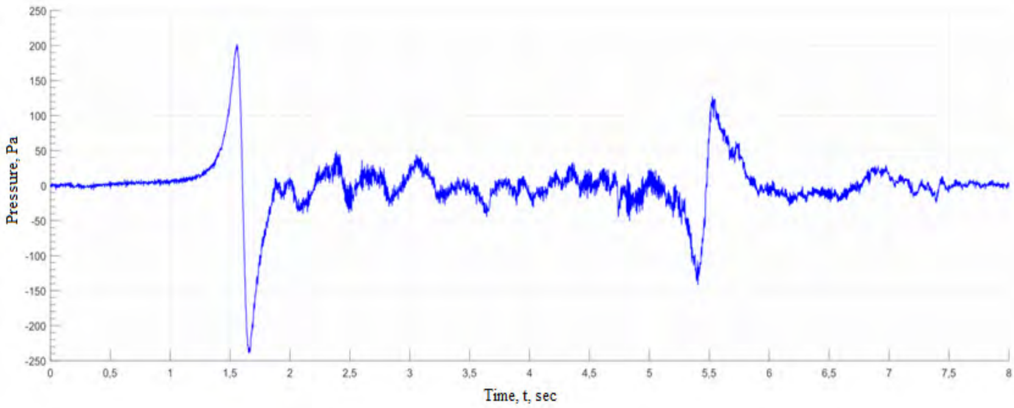
passage of a high-speed train. An example of a graph is shown in Pic. 11.

By processing the measurement results, distribution patterns of extreme values of overpressure and rarefaction pressure were obtained for speeds from 200 to 250 km/h, depending on the distance from the track axis and the height above the level of the rail head. An example of the distribution of excess pressure during movement of Sapsan electric train at a speed of 250 km/h is shown in Pic. 12.

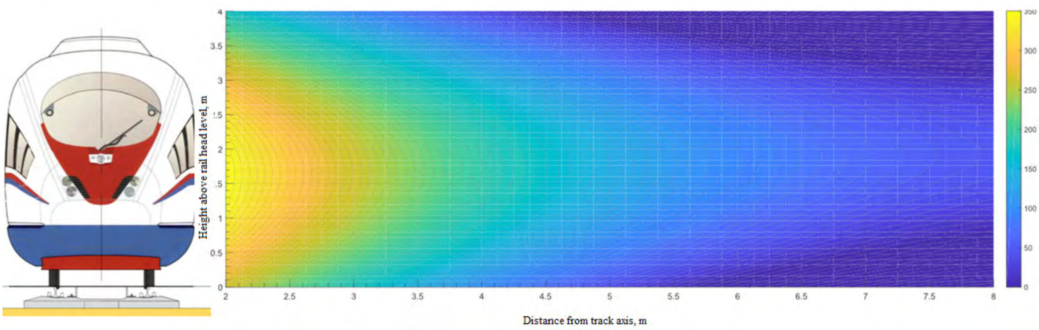
To verify the developed calculation models, the train movement conditions and measurement points were set that corresponded to the speed of motion and the locations of the sensors during full-scale measurements. The time step was set to match the measurement frequency of the sensors (1 kHz). Thus, train passages at speeds of 200, 220 and 250 km/h were simulated with pressure measurements at fixed points. Comparative patterns of pressure distribution at the points corresponding to the location of the head of the train for two calculation models are shown in Pics. 13–15.

The resulting images demonstrate a qualitatively similar pattern of pressure distribution around the train, but due to more detailed grid discretisation and elaboration of the boundary layer around the train, the model using the sliding grid method demonstrates a more detailed and accurate pressure distribution near the car surface, which directly affects the

Pic. 10. The process of measuring the aerodynamic impact from the Sapsan high-speed electric train [image made by the author].



Pic. 11. Graph of the change in the pressure value during movement of the Sapsan high-speed electric train at a speed of 250 km/h [performed by the author, [17]].



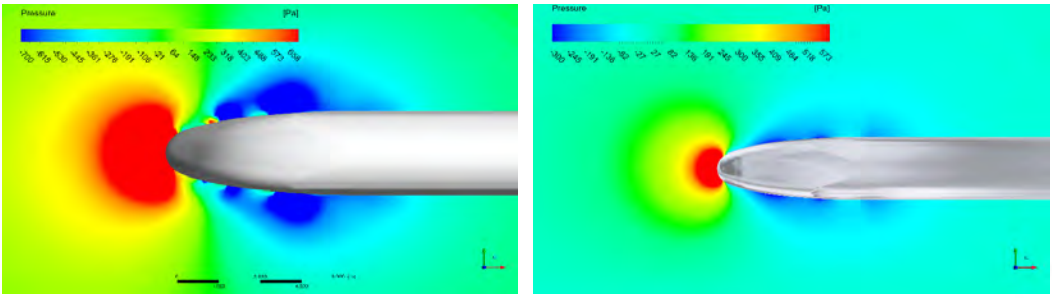
Pic. 12. Distribution of the overpressure value during movement of the Sapsan high-speed electric train at a speed of 250 km/h [performed by the author].

identification of the values of aerodynamic forces acting on the train.

The results of comparing the experimental and calculated values of extreme pressures at the measurement points are shown in Pic. 16 and Table 1.

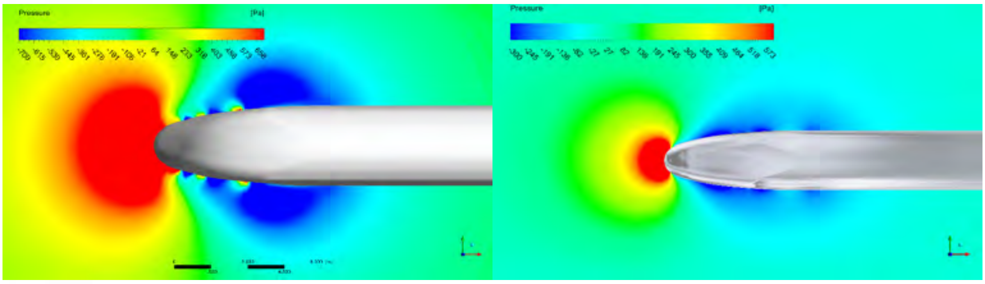
The spread of the discrepancy is determined by the local conditions of the terrain and the environment at the sites of experimental measurements (the presence in the immediate vicinity of the places of measurements of office premises, power supply facilities and devices, station and operational facilities). The maximum discrepancy is 15 %, the average discrepancy does not exceed 10 %.

Also, to verify the developed calculation models in a wider range of speeds, the results



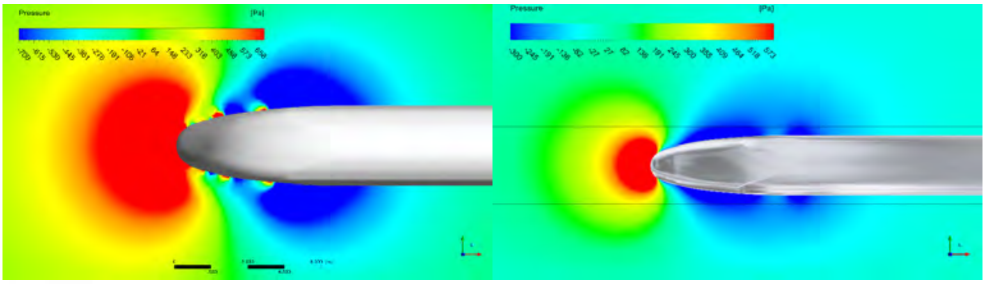
a) *b)*

Pic. 13. Pressure distribution near the first car of the design train at a height of 1,1 m at a speed of 200 km/h (a – immersed solid method, b – sliding grid method) [performed by the author].



a) b)

Pic. 14. Pressure distribution near the first car of the design train at a height of 1,1 m at a speed of 220 km/h (a – immersed solid method, b – sliding grid method) [performed by the author].



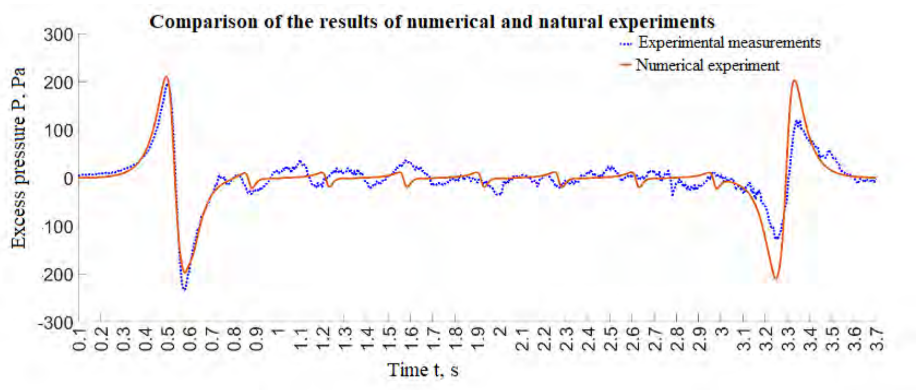
a) b)

Pic. 15. Pressure distribution near the first car of the design train at a height of 1,1 m at a speed of 250 km/h (a – immersed solid method, b – sliding grid method) [performed by the author].

Table 1

Results of comparison of experimental and calculated extreme pressure values [performed by the author]

Speed	Distance from track axis, m	Height above rail head level, m	Discrepancy, %			
			immersed solid model		sliding grid model	
			maximum pressure	minimum pressure	maximum pressure	minimum pressure
200	3,3	3,1	9	4	13	10
	3,4	2,15	13	12	10	14
	3,4	2,5	12	8	8	15
	3,8	2,6	14	2	15	11
	4	1,3	1	1	12	5
	7,1	4,2	9	12	4	14
	7,6	1,35	3	1	13	6
220	3,5	2,15	15	1	1	7
	7,5	3,1	13	13	15	10
	7,5	2,4	1	10	14	7
	8	2,6	14	9	10	2
	8,5	2,15	3	10	2	15
250	2,4	2,7	11	5	11	5
	3,1	2,4	14	15	3	12
	3,4	1,7	12	15	7	15
	4,2	1,5	5	15	13	5
	9,2	1,5	14	15	2	10



Pic. 16. Comparison of excess pressure values at the control and measuring point obtained numerically and experimentally for Sapsan high-speed electric train at a speed of 250 km/h (distance from the track axis is 3,1 m, height above the level of the rail head is 2,4 m) [performed by the author].

obtained in the software package were compared with the data of foreign experimental measurements of the aerodynamic impact during the passage of a high-speed train ICE3 at a speed of 300 km/h (Pic. 17) [18]. The discrepancy between the extreme values is no more than 8 %.

Thus, the verification results show that the developed calculation models have a sufficient validity and can be used in solving problems of aerodynamic interaction of high-speed rolling stock with the air environment and infrastructure facilities.

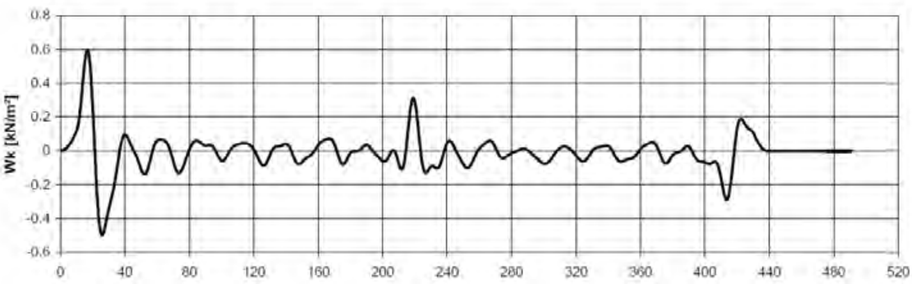
CONCLUSION

The article has considered various approaches to numerical modelling of the aerodynamic interaction of high-speed rolling stock, air environment and infrastructure facilities. The developed calculation models were verified based on experimental measurements of the aerodynamic impact of Sapsan high-speed electric train and the results of similar foreign studies. The largest discrepancy between the calculated and experimental values is no more than 15 %, which allows us to conclude that the developed models are sufficiently reliable.

Comparison of two different approaches (sliding grid method and immersed solid method) to modelling the aerodynamics of a moving train relative to stationary objects allows us to draw conclusions about the appropriateness of their application, depending on the problem statement.

So, to determine the magnitude of the aerodynamic force and moment acting on the cars of the design train, it is necessary to use the method of sliding grid, which makes it possible to form a boundary layer near the walls of the cars and obtain the most correct picture of the distribution of air masses and, as a result, reliable values of the impact on the rolling stock.

To determine the degree of aerodynamic impact on various infrastructure facilities, it is proposed to use the immersed solid method. This approach does not allow modelling the boundary layer around the walls of the design train and, as a result, obtaining reliable values of aerodynamic loads on the rolling stock. However, when determining the degree of aerodynamic impact



Pic. 17. Graph of the pressure value along the length of a high-speed electric train moving at a speed of 300 km/h [18] (the x-axis – the length of the electric train, y-axis – the pressure values).

on the infrastructure, this factor is not mandatory. Also, the immersed solid method requires significantly less computational and time costs, which makes it the most rational in solving problems of determining the aerodynamic impact on structures and facilities.

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