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Numerical investigation of aerodynamic action on track vicinity within the electric locomotive operation

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Abstract

The paper deals with the numerical investigation of aerodynamic loads on railway track vicinity within the passage of the train set consisting of the electric locomotive ŠKODA 109E and three passenger carriages. In agreement with requirements specified in TSI (Technical specification for Interoperability) railway safety standards following two different train operating modes were simulated – train passage in open space and train passage along the platform. In both the cases the train operates on a straight track with 200 km/h speed of motion, which is the maximum operational speed of the locomotive. The main results of the problem solution represent time-variations of pressure and velocity recorded in defined locations in track vicinity and a report of the aerodynamic force affecting the reference cylinder in a horizontal plane within the train passage. The values obtained are compared to the relevant reference values, which are published in TSI safety standards for the particular train operating mode.

Keywords: computational fluid dynamics, railway application, Technical Specification for Interoperability, aerodynamic loading, open air

1. Introduction

Locomotive 109E is primarily intended for priority trains operating not only in the Czech Republic, but on main corridors of the European Union. From the beginning the locomotive is designed with respect to the newest TSI (Technical Specification for Interoperability) safety standards [9] and valid Czech technical standards [1], [2], [3]. Not only because of that the locomotive complies with the most demanding European requests to railway operation safety.

Fig. 1. Locomotive ŠKODA 109E in colours of Czech Railways.

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From the external aerodynamics point of view, when the locomotive operates, aerodynamic transient incidences on the track vicinity are numerically and experimentally (after the vehicle prototype has been completed) investigated. The values of velocity and pressure amplitudes observed must not exceed the maximum health limits permitted in TSI safety standards.

2. Problem formulation

In the last edition of TSI railway safety standards [9] there have been specified three train operating modes with the following problems to be investigated:

(A) *Train operation in the open* (simulation and experiment)
(B) *Train passage through a single track tunnel* (simulation and experiment)
(C) *Crosswind effects in open air* (simulation)

This paper deals only with numerical investigation of the *(A)* train operating mode – *Train operation in the open*. This covers realization of two independent simulations, which include following problems to be investigated:

- Train passage in the open space
  - aerodynamic loads on track workers at the lineside
  - pressure loads in the open
  - pressure wave effects on a test cylinder
- Train passage along the platform
  - aerodynamic loads on passengers on a platform

The results of numerical simulation of *train passage through a tunnel* are introduced in [6] and [8].

3. Train composition model

As introduced in [9], when assessing conformity of locomotives or driving coaches, assessment shall be done on a basis of two arbitrary train compositions of minimum length 150m, one with leading locomotive or driving coach and one with the locomotive or driving coach at the end. For the computations the composition was reduced into the 93m long train composed of the electric locomotive ŠKODA 109E and three coaches, see fig. 2.

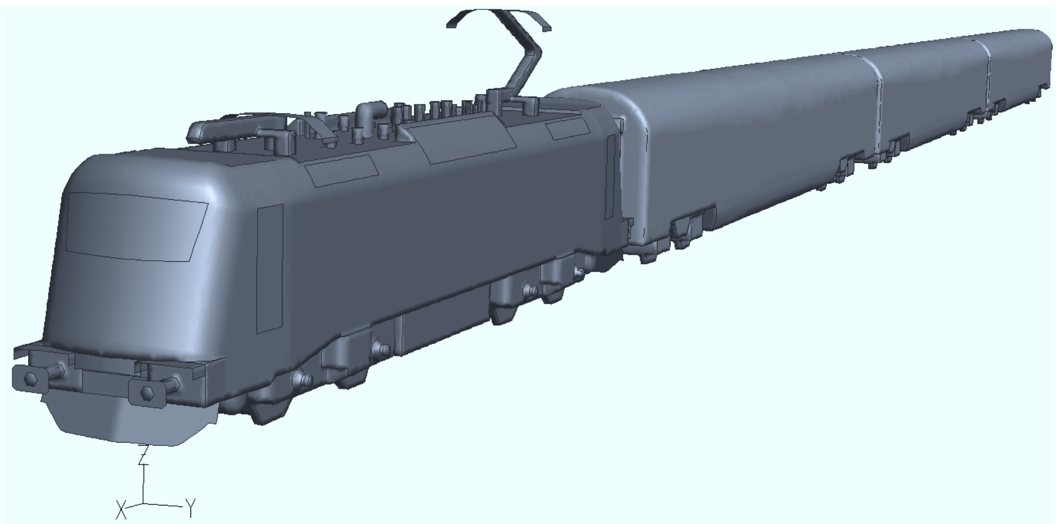

Fig. 2. Train model used in numerical simulations.

4. Domain geometry

The train model dimensions, the space required to acquire time-records of observed variables and the "sliding mesh" method used to enable the train time-dependent motion simulation are fundamental for the computational domain arrangement. The general outer dimensions of the domain are: length 543m, width 50m and height 20m.

Two modifications of the computational domain were made – for simulation of the train passage in the open and passage along the platform. In fig. 3 there are shown the differences between the domain cross-sections. The railway embankment and line profile as well as the platform level agree with the TSI safety standards [9].

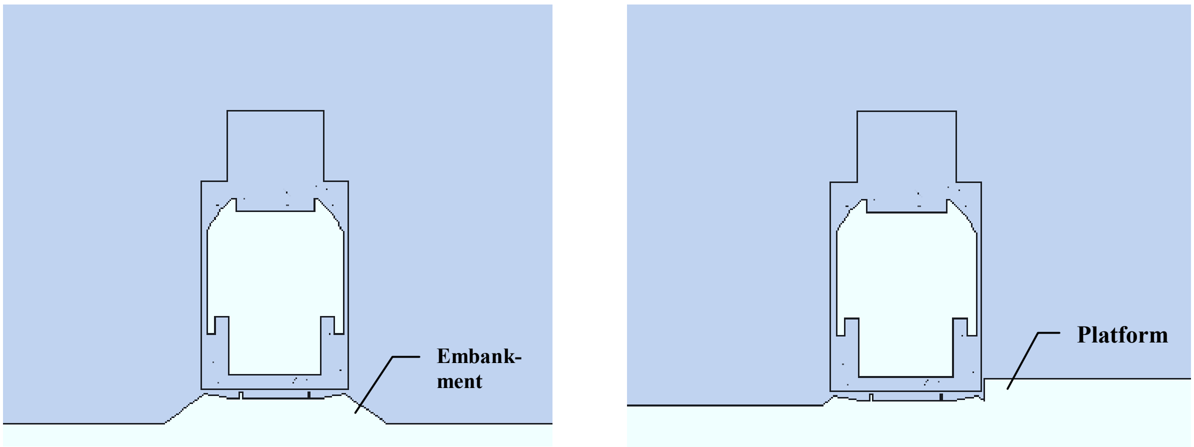

Fig. 3. Two modifications of the computational domain – for train passage in the open (left) and for train passage along the platform (right).

5. Computational grid

Gambit and Tgrid pre-processors were used for the domain geometry and computational grid construction. The computational domain was divided into several parts in order to be meshed separately. The closest neighbourhood was meshed with relatively fine tetrahedral elements while on the rest of the domain coarser hexahedrons were applied. General number of computational grid elements exceeded 2 million for both the simulations realized.

As described in [5], the grid quality was checked according to the maximum element's angular skewness criterion q_{EAS},

$$q_{\mathrm{EAS}} = \max\left[\frac{\alpha_{\max} - \alpha_e}{180 - \alpha_e}, \frac{\alpha_e - \alpha_{\min}}{\alpha_e}\right], \tag{1}$$

where $\alpha_{\max}$ is the greatest angle in the element, $\alpha_{\min}$ is the smallest angle in the element and α_{e} is the normalized angle of equiangular element, e.g. 90° for the square and 60° for the triangle. Regarding this criterion $q_{\mathrm{EAS}} < 0.95$ was found out, what illustrates satisfactory grid quality.

6. Numerical solution

All calculations mentioned were performed with usage of professional code Fluent version 6.3. Regarding to relatively lower velocities expected ($\mathrm{M} < 0.25$), the air flow was solved as an unsteady turbulent flow of incompressible viscous Newtonian fluid with the density $\rho_{\text{air}} = 1.225\ \text{kg/m}^3$ and kinematic viscosity $\nu = 1.7894 \cdot 10^{-5}\ \text{kg/ms}$. The "realizable" k - ε turbulent model with the default values of model constants was used to compute turbulent kinetic energy k and turbulent energy dissipation rate ε.

At the domain boundary following boundary conditions were set. On boundaries limiting the "open space" the constant atmospheric pressure $p_{\text{st}} = p_{\text{atm}} = 101325\ \text{Pa}$ was set. The rest of the domain boundary (the ground, surfaces of the locomotive, coaches, the track and embankment) were considered as a solid wall with the "no slip" boundary condition.

The constant-in-time 200 km/h straight movement of the train composition was enabled via "sliding mesh" model, which is implemented in Fluent code and particularly described in [4]. The value 200 km/h represents the maximum operational speed of the electric locomotive ŠKODA 109E.

For computations, the pressure-based solver of Navier-Stokes equations in 3D based on the unsteady implicit formulation of the second order upwind scheme was used. Fluent fixed time-stepping method was preserved for the unsteady solution. The size of the time-step $\Delta t = 0.009\ \text{s}$ corresponds with 0.5m forward translation of the train composition. 20 iterations per time step appeared to be enough for proper convergence.

The residuals of all equations solved dropped below the 10^{-3} ratio by far in each time step, below the 10^{-7} ratio for energy respectively. Another indicator of satisfying results is the difference between the general mass flow incoming into and outgoing from the computational domain. Within the solution, this value did not exceed an interval $\pm 1.5\ \text{kg/s}$.

7. Results overview

The results obtained from realized calculations are further introduced consequently in four subsections. Each subsection deals with one problem as formulated in section 2.

7.1. Aerodynamic loads on track workers at the lineside

According to TSI safety standards [9], the aerodynamic loads on track workers in railway track vicinity within the train passage are derived from air flow speeds recorded in 10 monitoring points (**V_69**, ***V_89***, …, ***V_249***) positioned lengthwise to the track with the 20m distance one to the next, 3.0m from the track centre and 0.2m above the top of the rail, see fig. 3.

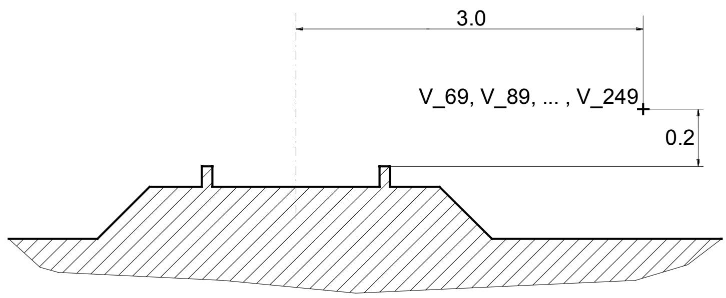

Fig. 4. Positioning and labelling of the velocity-monitoring points.

For the rolling stock with the maximum operating speed of 190 ÷ 249 km/h the train-induced air speed $u_{2\sigma}$ calculated from the obtained data must not exceed the $u_{2\sigma\,\text{ref}} = 20\ \text{m/s}$

reference value. $u_{2\sigma}$ represents the upper bound of the 2σ confidence interval of the maximum induced air speeds and is given by formula

$$u_{2\sigma} = \bar{u} + 2\sigma \ , \tag{2}$$

where $\bar{u}$ represents the mean value of all maximum induced air speeds u_j as monitored within the calculation and σ the standard deviation

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(u_j - \bar{u}\right)^2} \ . \tag{3}$$

In fig. 7 there are shown time-variations of velocity magnitude as monitored in two selected points (***V_69***, ***V_149***) within the train composition passage. While the characteristic first amplitude, caused by the locomotive head passage, does not change within the movement course and is identically monitored in all points, see fig. 7., further history of velocity is variable, including the moment and the value of maximum achievement. In most of the records the maximum is reached after the train tail passes by the wake behind the last coach, as, for example, in ***V_69*** monitoring point. The value $u_{2\sigma} = 17.2$ m/s obtained from the simulation satisfies the TSI [9] requirement.

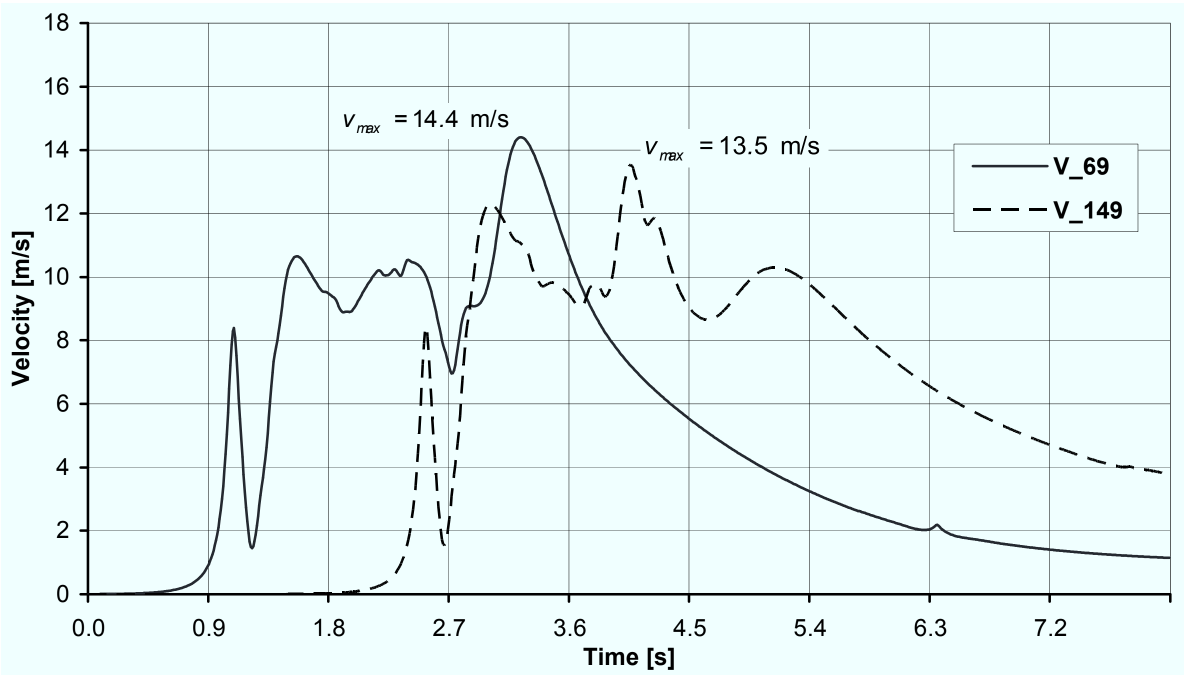

Fig. 5. Airflow velocity magnitude history monitored in points ***V_69*** and ***V_149***.

7.2. Pressure loads in open air

As introduced in TSI [9] safety standards for the train passage in the open, pressure loads at the track vicinity are monitored via 70 monitoring points, positioned in 10 groups lengthwise to the track with the 20m distance one to the next. In each point group the points are positioned equally in 7 height levels from 1.5m to 3.3m above the top of the rail and in the distance of 2.5m from the track centre, see fig. 6.

For rolling stock with the maximum operating speed of 190 ÷ 249 km/h the train-induced maximum pressure amplitude $\Delta p_{2\sigma}$ calculated from the obtained data must not exceed the $\Delta p_{2\sigma\,\mathrm{ref}} = 720$ Pa reference value.

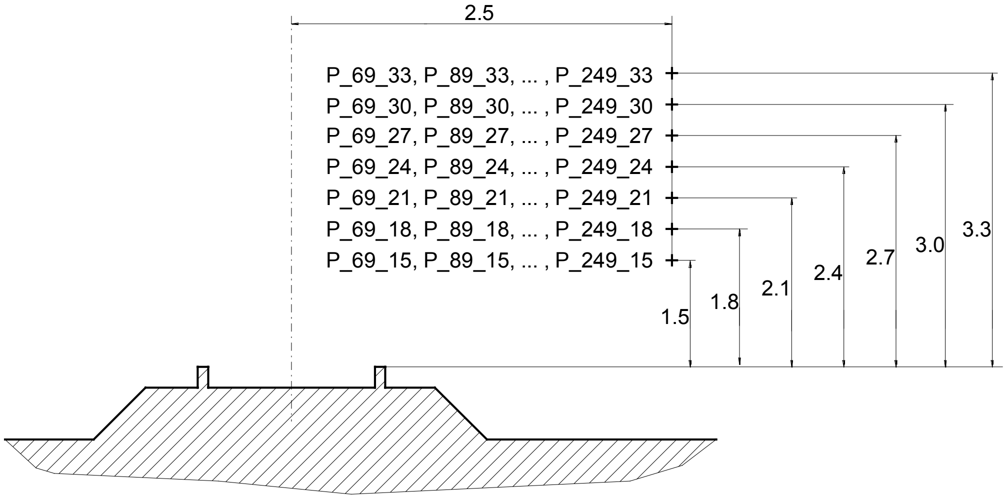

Fig. 6. Positioning and labelling of the total-pressure monitoring points.

For each monitoring level the value of pressure amplitude $\Delta p_{2\sigma}$ is derived from the relation

$$\Delta p_{2\sigma} = \overline{\Delta p} + 2\sigma \ , \tag{4}$$

where $\overline{\Delta p}$ represents the mean value of all maximum pressure amplitudes induced within the same level Δp_{j} and σ the standard deviation

$$\sigma = \sqrt{\frac{1}{\mathrm{N}-1}\sum_{\mathrm{j}=1}^{\mathrm{N}}\left(\Delta p_{\mathrm{j}} - \overline{\Delta p}\right)^2} \ . \tag{5}$$

From the amplitudes $\Delta p_{2\sigma}$ (obtained from all 10 points of each level separately) is then the maximum pressure amplitude $\Delta p_{2\sigma\max}$ found out.

In fig. 7 there are demonstrated total pressure time-variations within the train passage monitored in one group of points (points with the different height above the top of the rail).

As expected, the pressure history shows the maximum pressure-amplitude within the locomotive head passage, lower amplitudes are recorded by the train tail passage and there can be also identified pressure variations caused by the interspaces between the vehicles. In general, the highest amplitudes were found out in the lowest positioned points (in the height of 1.5m above the top of the rail). The value $\Delta p_{2\sigma\max} = 729.5$ Pa obtained from the simulation results slightly exceeds the TSI [9] requirement.

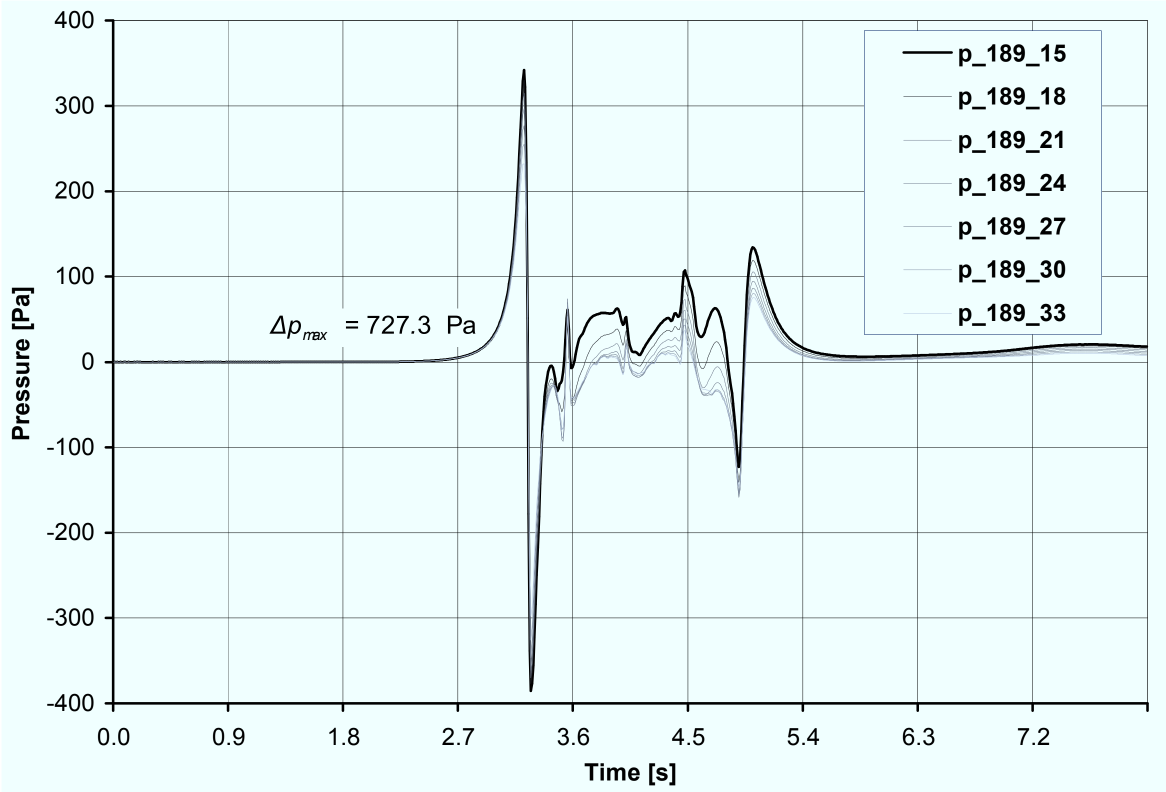

Fig. 7. Total pressure history monitored in 7 points with different height above the top of the rail.

7.3. Pressure wave effects

Pressure wave effects, which act on persons in track vicinity within the train passage in the open, are monitored on a test "dummy". This figure is in agreement with TSI [9] substituted by a rotational cylinder with the bottom diameter of 0.4m and the height of 0.92m. The cylinder position relative to the rail is evident from fig. 8.

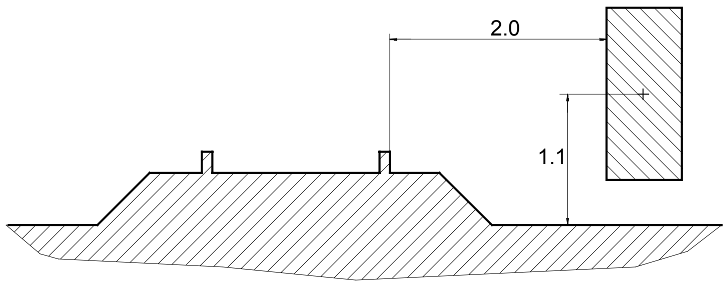

Fig. 8. Position of the test dummy (cylinder) relative to the rail.

The maximum value of aerodynamic force vector $|\boldsymbol{F}|$ acting on the reference cylinder body in the horizontal level is the only value to be observed in this section. In fig. 9. there is shown the time-variation of aerodynamic force vector magnitude $|\boldsymbol{F}|$ and the force components in the train motion direction (F_x) and in the direction normal to the train motion direction (F_y), respecting that

$$|\boldsymbol{F}| = \sqrt{F_x^2 + F_y^2} \quad . \tag{6}$$

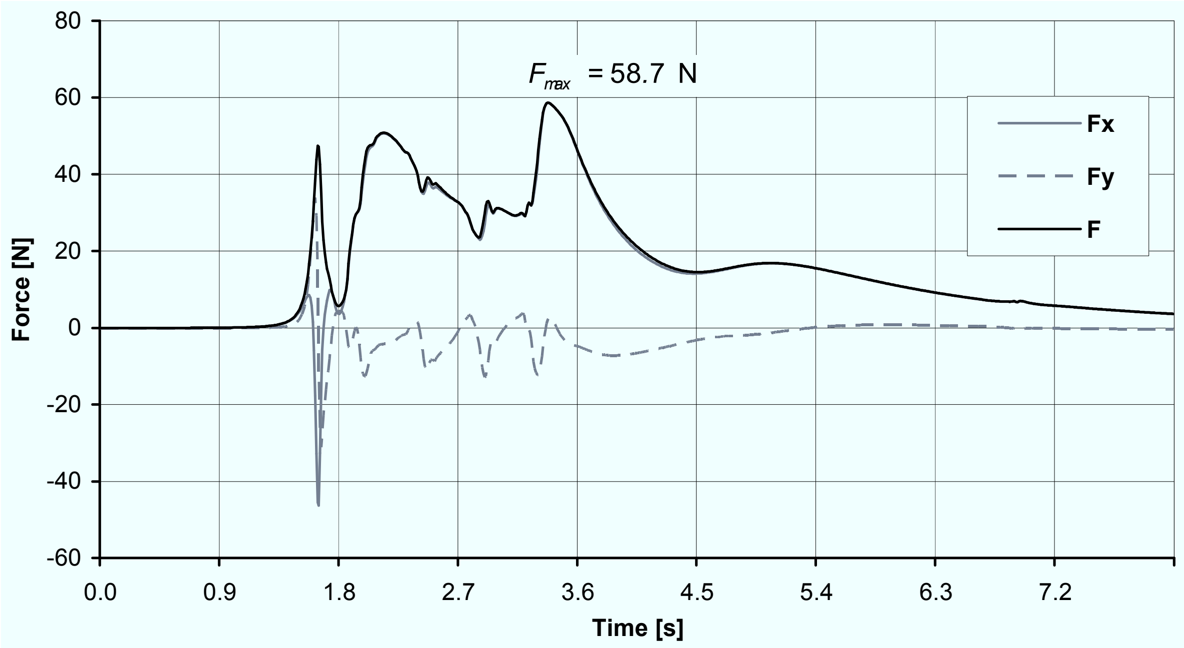

Fig. 9. Time-dependence of aerodynamic force vector magnitude and its components effecting on the reference cylinder.

7.4. Aerodynamic loads on passengers on a platform

According to TSI safety standards [9], the level of aerodynamic loads on persons on platforms is controlled by monitoring the airflow speed in 10 monitoring points (***V_69_plat***, ***V_89_plat***, …, ***V_249_plat***) positioned lengthwise to the track with the 20m distance one to the next, 3.0m from the track centre and 1.2m above the platform level, see fig. 10.

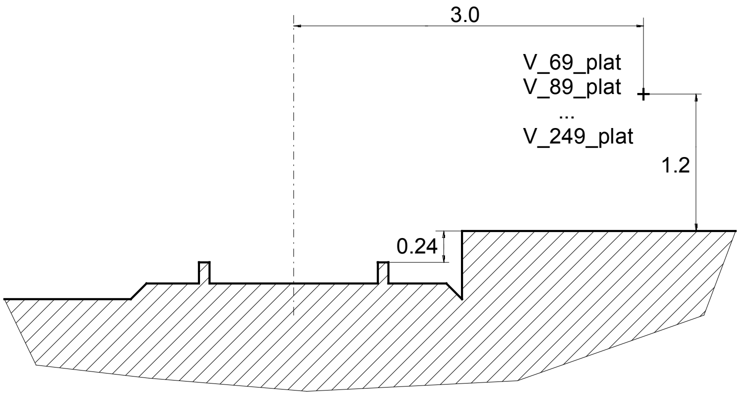

Fig. 10. Positioning and labelling of the velocity-monitoring points.

Similarly as introduced in section 7.1., for rolling stock with the maximum operating speed of 190 ÷ 249 km/h the train-induced air speed $u_{2\sigma}$ calculated from the obtained data according to equation (2) must not exceed the $u_{2\sigma\,\mathrm{ref}} = 15.5$ m/s reference value.

In fig. 11 there are shown time-variations of velocity magnitude as monitored in two selected monitoring points (***V_69_plat***, ***V_169_plat***) within the train composition passage. In the same figure there is also marked the reference value $u_{2\sigma\,\mathrm{ref}} = 15.5$ m/s specified in the TSI [9].

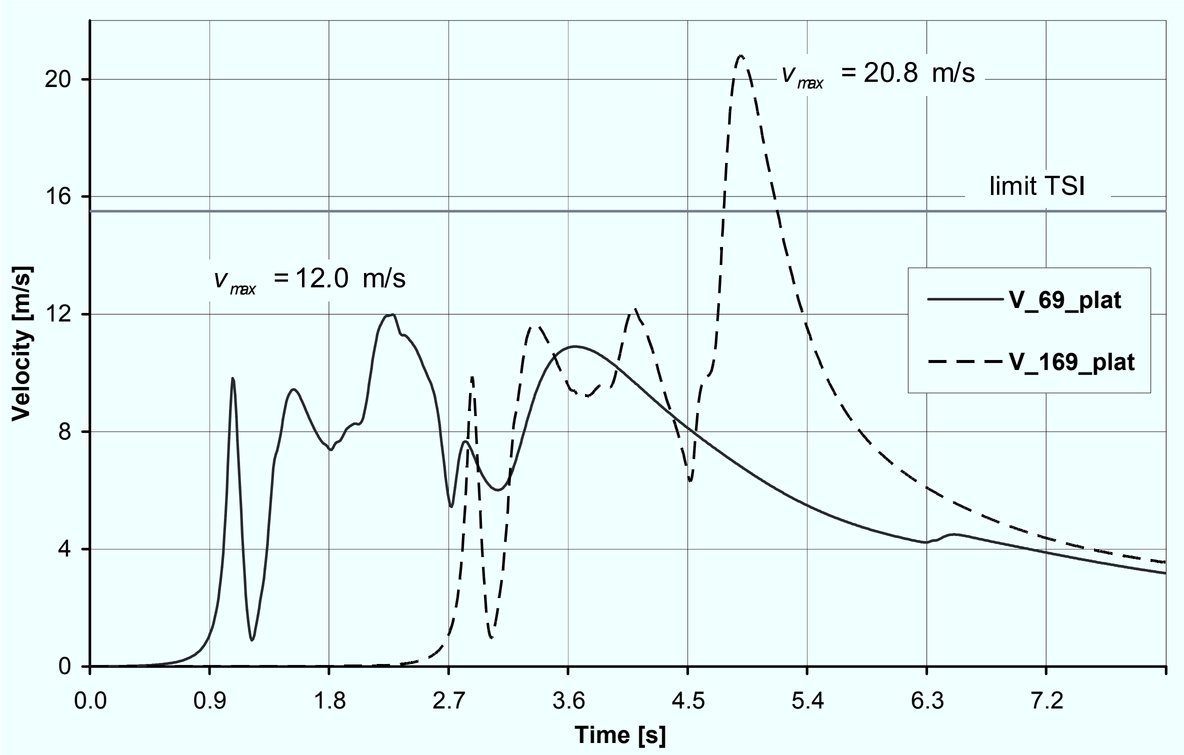

Fig. 11. Airflow velocity magnitude history monitored in points ***V_69_plat*** and ***V_169_plat***.

Similarly as in the case of passage in the open, also in the case of passage along the platform the initial gust can be identified identical in all data records. More significant detection is that from 10 records in 3 cases exceeding of the reference velocity magnitude $u_{2\sigma\,\mathrm{ref}}$ occurred, as shows for example the time-variation of velocity recorded in point ***V_169_plat*** in figure 11. The airflow velocity $u_{2\sigma} = 20.3$ m/s calculated from the obtained data exceeds the prescribed value of the $u_{2\sigma\,\mathrm{ref}}$.

8. Conclusion

The train-induced aerodynamic loads on track vicinity represents one of the essential criterions of the TSI [9] to assess conformity of the locomotive ŠKODA 109E. According to the TSI safety standards [9] two operating modes have been simulated – the train passage in the open air and the train passage along the platform. In both the cases the train composition consists of the locomotive ŠKODA 109E and three coaches and operates on a straight track with the locomotive maximum operating speed 200 km/h.

The main results from the simulations represent time-variations of pressure and velocity recorded in defined locations (points) in train vicinity and the record of the aerodynamic force vector magnitude, which effects on the reference cylinder in the horizontal plane within the train passage. The values obtained are compared to the relevant reference values, which are published in the TSI safety standards [9] for the particular train operating mode, see tab. 1.

The object of further work in the arena of external aerodynamics of the loco ŠKODA 109E is the numerical investigation of the train-composition passage through a single-track tunnel [6], where the external load on the locomotive surface and the pressure conditions inside the tunnel are primarily monitored within the train motion. After the prototype of the locomotive ŠKODA 109E is completely produced, aerodynamic loads on the track vicinity within the train passage in the open space, along the platform and through a single-track tunnel will be also experimentally verified on the real track. The technical reports containing both the results of numerical simulations [6], [7] and measurements will be integrated into the collection of technical documentation, which will be given to the assessment process in order to get the certificate of the locomotive ŠKODA 109E interoperability.

	TSI [9] - reference value	**Calculation result**
Trackside induced air speed $u_{2\sigma}$ [m/s]	≤ 20.0	17.2
Trackside induced pressure amplitude $\Delta p_{2\sigma}$ [Pa]	≤ 720.0	729.5
Maximum induced aerodynamic force on the reference cylinder $\lvert \boldsymbol{F} \rvert$ [N]	≤ 185.0	58.7
Trackside induced air speed on the platform $u_{2\sigma}$ [m/s]	≤ 15.5	20.3

Tab. 1. Summary of the reference values required by TSI and results obtained from numerical simulations.

Acknowledgement

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