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Research of interaction of the "train – bridge" system with bridge deck resonant vibrations

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Abstract. When designing bridges on high-speed railways, special attention should be paid to ensuring the safety of train traffic and the comfort of passengers. On high-speed railways, the proportion of the length of bridge structures in the composition of the entire route is much larger than on conventional railways, which makes the present study relevant. In this paper based on numerical simulation, the results of the study of the motion of a high-speed train along bridge structures in the resonance mode of vibrations are presented. In this formulation, special attention was paid to the control of dynamic phenomena at the level of the "wheel-rail" contact. The dynamics of loose parts of the train car determines the magnitude of the contact force, which in turn characterizes the possible detachable movement of the wheel, which is inadmissible for the safety of the train. Analysis of the obtained results, using the example of a 50 m long simple span structure developed for the Moscow-Kazan high-speed railway, allows us to conclude that the resonant nature of the vibrations of simple beam is not a critical phenomenon.

1 Introduction

The design of bridge structures on high-speed railways taking into account the dynamic interaction of the "bridge-train" system is a priority area of research [1-4]. Despite the successful experience in the construction and operation of high-speed railways with speeds up to 350 km/h, as well as availability of extensive researches of the bridge structures dynamics, the problems of interaction of train with bridge structures are extremely important, and the solution of these issues is one of the key criteria that determine the fundamental possibility of ensuring the train movement.

Actually, the interaction of the two subsystems, the bridge and the train moving along the structure, is a nonlinear dynamic problem [5]. In accordance with the goals and trends of bridge engineering development, traditionally, most researches have been focused on studying the dynamic response of the bridge to the action of the live load [4]. Frequently, when solving dynamic problems (primarily typical for conventional railways) requiring research only the reaction of bridge decks, the live load from the rolling stock, can be represented by a relatively simple model in the form of a system of concentrated forces corresponding to the scheme of the train moving at a constant given speed [6, 7]. Such a load model, in the form of "moving forces", can't be used to solve dynamic problems,

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taking into account the fluctuations of the train, which is especially important for high-speed railways. In these cases, the live load model must take into account the mechanical parameters of the rolling stock as a dynamic system to adequately describe the dynamic processes of interaction of the joint system "bridge-train".

The nature of the rolling stock movement on bridge structures differs significantly from the movement conditions on the embankment. When moving over the bridge decks train coaches make complex vibrations, the main forms of which are jumping, that is to say car body vertical movements with the same deformation of the springs on the boogies; galloping, that is car body rotational movements relatively to the transverse axis with the same and opposite in the deformation directions of the springs on the boogies.

Vibration features of train coaches when moving on bridges are primarily associated with the deformability of spans, which receive the bend deformation under the live load. Moving along the profile deformed under load on the construction, the cars will experience a kinematic impact. At certain train speeds at the same (multiplicity) excitation frequency and the vibration frequency of the car body, resonance phenomena can occur in the coaches of the train [8, 9].

The nature of the movement and the dynamic response of the train coaches is mainly determined by:

- kinematic excitation parameters (number and static spans scheme, span length, flexural rigidity (deflections amplitude under live load), angle of gradient change over piers, track and wheels irregularities);
- train speed;
- train coach parameters (elastic and viscous elements of primary and secondary suspension, distribution and magnitude of sprung and unsprung masses);
- track characteristics (stiffness and damping properties of the rail pads, ballast or ballastless slabs).

The main parameter characterizing the dynamic system "coach" can be considered the natural vibrations frequency of the first vertical forms (jumping and galloping). The natural vertical vibrations frequency of the coach in jumping in the gross state (fully equipped car with working materials, staff and passengers) of the high-speed train "Sapsan" (Velaro RUS) is 0.60 Hz, galloping 0.67 Hz, and in the state of the container (fully equipped car with working materials, staff and without passengers) is 0.56 Hz, galloping 0.65 Hz. Thus, for modern high-speed trains, the natural vibrations frequency of the car body is practically independent of the coach fill, what is explained by the presence of the secondary pneumatic suspension, the rigidity of which also varies depending on the magnitude of the perceived load.

We introduce the concept of the coach resonant speed equal to the span length - coach vibration frequency product. The speed at which the kinematic effect has a frequency equal to the coach natural frequency [8]:

$$V_{coach}^{resonance} = \frac{f_{car} \cdot L}{k}, \text{where } k = 1,2,3... \quad (1)$$

where $V_{coach}^{resonance}$ - coach resonant speed on bridge;

f_{coach} - coach natural vibration frequency;

L - span length.

Using the formula (1), we construct the dependence of the critical (resonance) speeds of the high-speed coaches for different spans lengths (Fig.1).

At the same time, at high train speeds, it is possible to excite resonant vibrations of the bridge decks. In this case, the main source of forced vibrations excitation of the bridge decks is the action of moving axial forces corresponding to the high-speed train scheme.

The parameter characterizing the dynamic effect of the live load is the excitation frequency, which varies linearly depending on the train speed. When the excitation frequency is close to the bridge deck natural frequencies, resonance vibrations occur [6, 7].

According to this conclusion, it's possible to determine the "critical" train speeds when resonant phenomena of simple beam bridge will be observed (Fig.1):

$$V_{beam}^{resonance} = \frac{f_1 \cdot d}{k}, \text{where } k = 1,2,3... \tag{2}$$

f_1 - the first simple beam bridge natural frequency (considered the range of natural frequencies, recommended by codes [10-11]);

d - coach length of the train (for "Sapsan" 26,175 m).

It should be noted that the possibility of resonant vibrations excitation of the bridge decks is due not only to the action frequency, but also to its amplitude, which significantly decreases with ratio increasing of the span length to the coach length. So for the spans longer than 60 m, resonance vibrations are practically not appeared [4, 6].

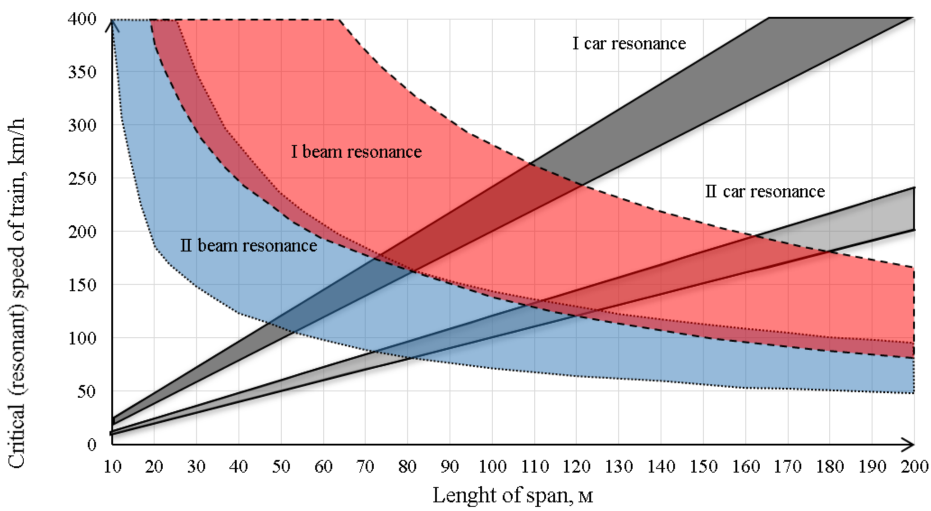

Fig. 1. Dependence of critical (resonant) speeds of coaches and bridge deck for different spans lengths.

We can conclude that at high speeds (more than 300 km/h) the main resonance of the high-speed coaches is realized when moving over the bridge decks with a length more than 120 m, and the bridge decks resonance vibrations are excited in spans up to 60 m. Thus, we can conclude that the synchronous excitation of the coaches and bridge decks resonance vibrations is impossible in practice.

At the same time, it is interesting to study high-speed train movement along bridge structures in the resonant vibrations mode. In this formulation, special attention should be paid to the dynamic phenomena control at a level of the wheel-rail contact. The dynamics of unsprung masses of coach determines the contact force amount, which in turn characterizes the possible separation of the wheel movement, which is unacceptable under the condition of ensuring the train safety [12].

2 Problem statement

During the research, the numerical calculations of dynamic interaction of high-speed train (Velaro RUS "Sapsan") and unified reinforced concrete bridge decks with a length of 50 m, developed by "Institute "Giprostroymost" (Moscow) for the high–speed railway "Moscow-Kazan" (Fig.2).

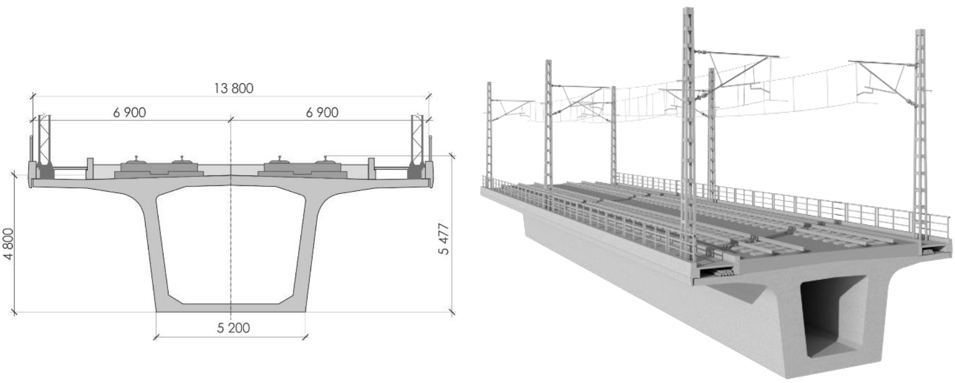

Fig. 2. Unified double-track split beam span structure of box section from prestressed concrete with full length of 50.0 m for high-speed railway "Moscow-Kazan".

The choice of the bridge decks is determined by the value of its first natural frequency in the vertical bending form of vibrations, which on average (taking into account the variation of constant loads from its own weight and the ballastless track) is 3.18 Hz. This fact determines the value of the critical (bridge decks resonance) speed of the high-speed train "Sapsan" (Velaro RUS) equal to 300 km/h.

The track on the bridge with ballastless slabs, in this formulation of the problem was not simulated.

During the calculations determined wheels and characteristic train body points trajectories, vertical accelerations in the coaches of the train and force in the contact "wheel-rail". During the study, the train movement on a three-span bridge structure with unified decks under the scheme of 3x50 m is considered.

In the design model, the bridge deck were approximated by spatial beam finite elements taking into account the real stiffness, inertial characteristics and damping parameters. The validity of this simplification in comparison with the models of flat finite elements is proved by the calculated values correspondence of the basic natural frequencies of vibrations for the first (basic) forms. At the same time, the use of a beam finite elements model significantly reduces the dimension of the problem, and, consequently, the calculation time.

The choice of train model is determined by the requirements to the results accuracy and detail. The main purpose of this work is to study the coaches vertical vibrations and their features while moving by the bridge decks in the resonant vibrations mode. Thus, a flat train model was chosen (Fig.3), and the possibility of transverse vibrations was provided by elastic elements of equivalent horizontal stiffness corresponding to the real parameters of the coach suspension.

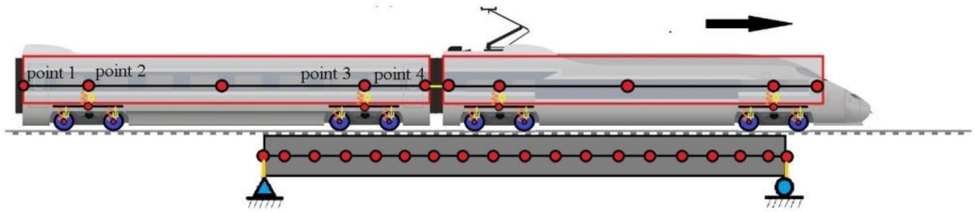

Fig. 3. Interaction model of "bridge-train" system.

The model of high-speed train is represented by the car body beam elements, which has a flexural stiffness corresponding to the cross section, the frames of boogies and wheelsets, which were taken absolutely rigid. All wheels tape lines radiuses are the same, the wheels roll without slipping and its tread surface is absolutely smooth. The car body has a two-stage suspension (Fig. 4) (the primary "wheelset - boogie" and the secondary "boogie - car body"), each of which is characterized by the rigidity and damping of the vibration dampers. Vibration dampers (hydro dampers) are modeled by equivalent elements with viscous resistance. First stage elastic suspension is provided by springs and the second – by pneumatic springs [8].

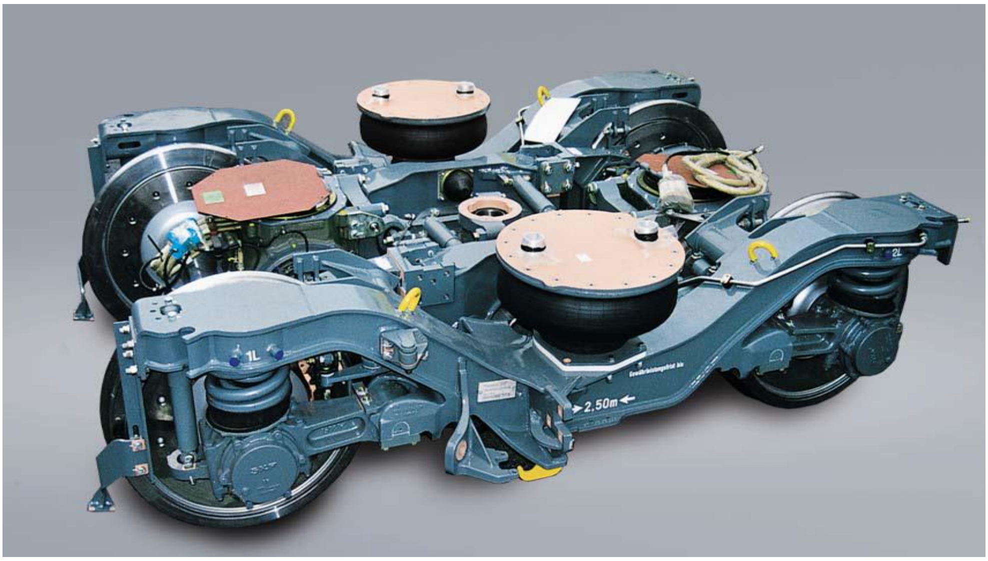

Fig. 4. Boogie of high-speed train "Sapsan" (Velaro RUS).

To take into account the effects of the interaction of high-speed train with bridge decks, each wheelset is represented by a node associated with the construction by an elastic element that simulates the contact "wheel - rail". The above mentioned moving contacts "springs" determine the possibility of obtaining a solution of the problem in the formulation of two dynamic systems "train - bridge" interaction. The masses distribution in a single dynamic system is determined with regard for the change in the position of the train in time. The position of the "contact nodes" of the model is also determined by the relative displacement of the moving train and the deformed bridge deck.

3 Analysis of dynamic interaction of high-speed trains while calculating bridge structures

As it was mentioned earlier, the case of high-speed train movement by bridge in the resonant vibration mode was considered during the study. Thus, when passing the high-speed train "Sapsan" (Velaro RUS) at speed of 300 km/h in the unified reinforced concrete bridge decks with a total length of 50,0 m, resonance vibrations are develop (Fig.5).

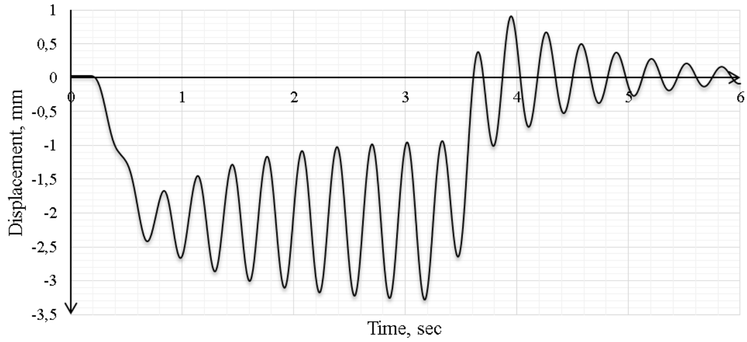

Fig. 5. Vertical displacements in the middle of the bridge span with a total length of 50.0 m while moving of a high-speed train "Sapsan" (Velaro RUS) at a resonant speed of 300 km/h.

The results of dynamic calculations of the high-speed train "Sapsan" (Velaro RUS) and unified concrete bridge decks at their resonance vibrations interaction are selectively presented below (Fig.6-9).

The trajectories of the movement of the wheels of the high-speed train car, shown in Fig. 6, due to the passage of the train along the chain of split spans in the resonant mode of oscillation, are of a complex nature. Unlike non-resonant speeds, when the trajectory of the wheels of the train cars is close to a half-wave of a sinusoidal length equal to the length of the span [11], in the case under investigation, the superficial structure oscillations are superimposed on the total static deflection of the structure under load. It should be noted that the maximum wheel movements of the rear boogie (axles 3 and 4) exceed similar values for the front boogie (axles 1 and 2). The angles of the fracture of the profile of the trajectory trajectories of the axles of the rear boogie also exceed the values for the front boogie of the car.

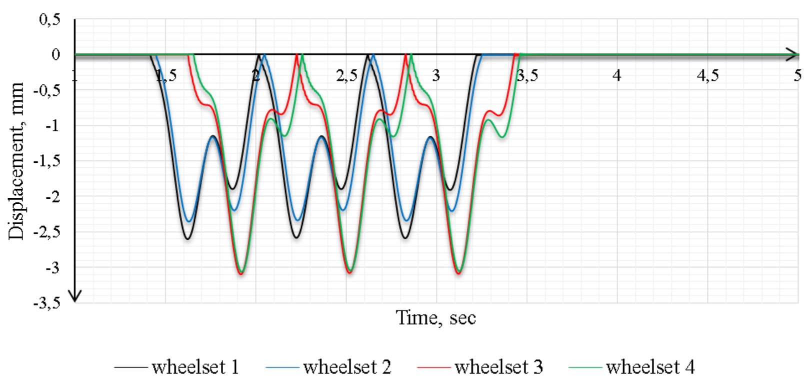

Fig. 6. The trajectory of the wheelsets of the train "Sapsan" (Velaro RUS) coach № 5 when passing on the bridge (3x50 m) at speed of 300 km/h

Graphs of vertical displacements of the characteristic points of the body of the average car of the train (see Fig. 3, 7) allow observing body oscillations close to the type of galloping with opposite deformations of the springs on the boogies.

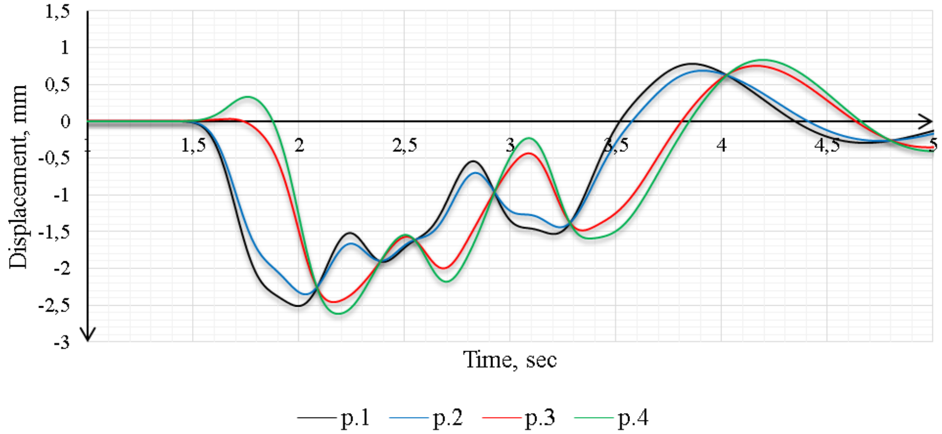

Fig. 7. Vertical displacements of characteristic points of the car body №5 train "Sapsan" (Velaro RUS) when passing on the bridge (3x50 m) at speed of 300 km/h

In spite of the fact that in the present study the case of the train's motion along the spans in the resonance mode of oscillations is considered, the acceleration of the car body presented in Fig. 8 is characterized by values in the range from -0.1 to 0.1 m / s^2 and doesn't exceed the values regulated by the standarts by the condition of ensuring the comfort of passengers [14]. The obtained values correspond to the "very good" smoothness index, which is explained by the efficient operation of the high-speed train hanging system.

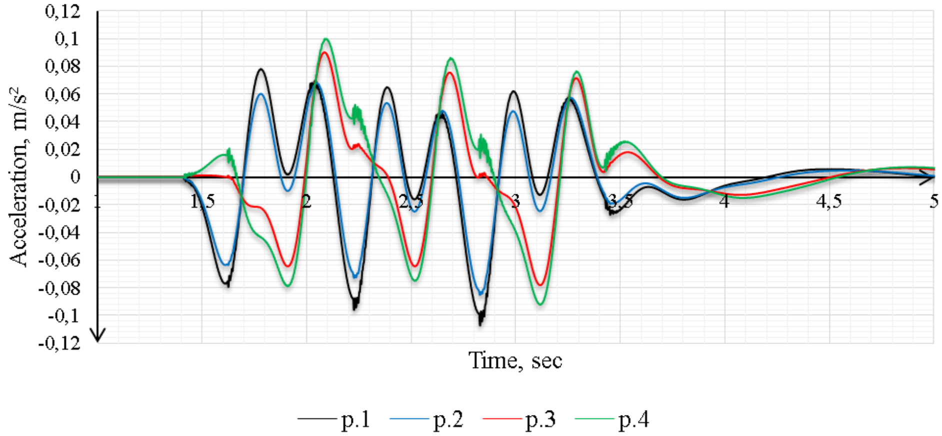

Fig. 8. Vertical accelerations of characteristic points of the car body №5 train "Sapsan" (Velaro RUS) when passing on the bridge (3x50 m) at speed of 300 km/h

On the graphs of the change in the forces at the wheel-rail contact, shown in Fig. 9, when the car passes through the profile fractures over the supports, a local increase is observed, caused by kinematic pulses (Fig. 6). The sharp increase in contact forces is quickly quenched in the damping elements of the car's suspension. The dynamic addition to the magnitude of the contact force in this case reaches 14%. Perhaps even more important is the "unloading" dynamic additive, which does not exceed 17%.

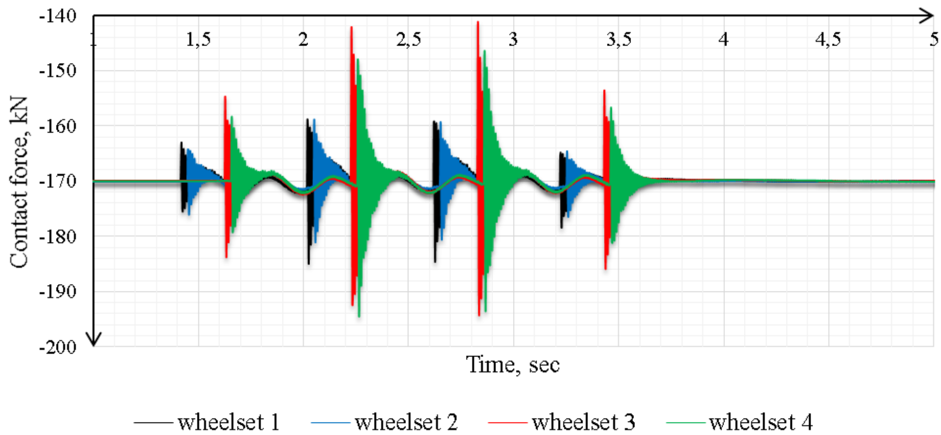

Fig. 9. Contact effort "wheel - rail" for the car body № 5 train "Sapsan" (Velaro RUS) when passing on the bridge (3x50 m) at speed of 300 km/h

The presented results of modeling the dynamic interaction of a high-speed train and bridge decks in the resonant mode of oscillations make it possible to observe the non-discontinuous character of the movement of the wheels and the availability of appropriate stocks. The values of the controlled parameters (acceleration in the train cars, the contact "wheel-rail" force) do not exceed the standard values, which provides a high level of passenger comfort, stability and safety of high-speed rolling stock.

4 Conclusion

When the train is moving, the detachable wheel movement, which is unacceptable under the condition of ensuring the safety of the train, is not observed. The ratio of dynamic and static efforts on the contact "wheel - rail" is in the range of 0.83...1.14, which does not exceed the value established by the technical standards. Acceleration in the train coaches also do not exceed the values established by the condition of ensuring the comfort of passengers.

It should be noted that the main source of vibrations excitation of the train coaches when moving on the bridges deck are changes of gradient over the pier, which imposes known limitations to the vertical stiffness of the span structures.

The analysis of the results, using the example of a unified beam with a length of 50 m, allows us to conclude that the resonance character of the simple beam vibrations at high train speeds is not a critical condition for ensuring the safety of train traffic and the comfort of passengers.

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