Design of Dynamic Parameters for Simple Beam Bridges on High-Speed Railways

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Abstract. The article describes a technique of determining the maximum accelerations of beam span structures arising from vibrations of the action of high-speed trains. The reliability of the proposed methodology is confirmed by the results of numerical modelling of the passage of high-speed trains on spans with different speeds. The proposed dynamic calculation algorithm is based on the connection between the maximum acceleration of a span, its stiffness and inertial characteristics, the length of the span and the parameters of a high-speed train. As a result of the research, requirements were received to limit the minimum mass of spans with the condition that the permissible vertical acceleration of the span is not exceeded (3.5 and 5.0 m / s2 for ballast and ballastless bridges). Based on the presented results, recommendations were developed for limiting the lower limit of the natural frequencies of oscillations of simple span structures, that are different from the recommendations of the International Union of Railways (UIC), designed for speeds less than 250 km/h and given in the Eurocode. The presented limitations of the lower limit of the natural frequencies of the oscillations of the span structures (10 to 30 m in length) make it possible to assign the main design parameters at the initial design stage in such a way as to minimize the dynamic impact of the mobile load at train speeds of up to 400 km/h. The proposed recommendations on the assignment of a minimum mass of span structures and the limitation of the lower limit of the natural frequencies of oscillations of simple span structures are of great importance and can be used in determining the main constructive parameters. Accounting for these recommendations significantly cuts the labor costs for de-sign and reduces the likelihood of possible adjustments after performing dynamic calculations.1. Introduction

1. Introduction

Currently, the design of bridge structures on high-speed railroads is performed on the basis of numerical modeling [1-6]. It should be noted that the analysis of dynamic tasks in software systems implementing the finite element method (FEM) requires considerable time-consuming, as a result of which the design process acquires an iterative character. To reduce labor costs for the design and optimization of decisions, an analytical approach to the actual task of the dynamic interaction of span structures and rolling stock at high speeds is needed [7, 8].

2. Problem statement

While train moving across the bridge variable force effect is transmitted from vehicle through wheel pairs to deck. At high train speeds the force action frequency can coincide with the frequencies of natural oscillations, that can lead to resonance oscillations of structures [4-5]. The described dynamic effects lead not only to an efforts increase in the elements of bridge structures, but also have an adverse effect on the stability of the span and the comfort of passengers during the train movements across bridges on high-speed railways [13,15]. The need for continuous monitoring of the dynamic response of span structures during the movement of high-speed trains with velocities up to 350 km / h was placed at the basis of the monitoring system for engineering structures at the Moscow-Kazan HSR in Russia [16].

Thus, the primary tasks in the design of bridge structures on high-speed railways are:

- pursuance of criteria of deck stability (limiting maximum vertical acceleration of the span structure) [1,8,9];
- ensuring the comfort of passengers while driving a train across a bridge [6,11,12];
- pursuance of criteria of an effort amount at the contact "wheel – rail" [14,15,17,18];
- determination of the dynamic coefficients to the temporary load while calculating the elements of the bridge structure [5,7,8].

Since the basic type of span structures in the construction of HSR is simple beam spans, for its calculation a load model in a form of a group of constant forces appropriating to the scheme of a high-speed train (the "mobile forces on a structure" model) is used. The results quantitatively and qualitatively describe the dynamic work of the structural elements of the span and require minimal labor [3-5,7]. Verifications on the safety criterion (rationing of the minimum amount of force on the "wheel – rail" contact) and the comfort of passengers (rate setting of the maximum vertical accelerations in the train) in this case are justified by limiting the vertical rigidity of the span structures [6,11].

3. Analysis of the dynamic effect of high-speed trains in calculation of bridge structures

High-speed trains with the length X_n (the distance between the first and the last axis) can be represented as a sequence of n loads Pi, whose abscissa is denoted by xi (the distance between the load P_i and the first axis). For the research, the excitation function due to the moving axial loads can be expanded in a Fourier series like [8,9]:

$$P(t)=\frac{2}{X_n}\int S_0(\lambda)\left(\cos\frac{2\pi Vt}{\lambda}+\sin\frac{2\pi Vt}{\lambda}\right)d\lambda \quad (1)$$

where λ is the excitation wavelength, m

$$S_0(\lambda)=\sqrt{\left(\sum_{i=1}^{n}P_i\cos\frac{2\pi x_i}{\lambda}\right)^2+\left(\sum_{i=1}^{n}P_i\sin\frac{2\pi x_i}{\lambda}\right)^2} \quad (2)$$

where S_0 (λ) is the excitation of a train and can be regarded as a dynamic characteristic of a train.

With this representation of the excitation function, it is possible to simplify the procedure of dynamic calculations for simple beams. Using the calculated parameters, it is possible to obtain the maximum vertical acceleration in the middle of the span when the train moves with velocity V. This technique can be used only for the resonant mode with respect to the first bending mode of oscillations.

The maximum value of the acceleration a_{max} is determined by the product of the following terms [8,9]:

$$a_{\max}=C\cdot A(L/\lambda)\cdot G(\lambda) \quad (3)$$

where C is a parameter that depends on the mass of the span structure:

$$C=\frac{4}{m\pi} \quad (4)$$

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A (L / λ) depends only on the length of the span L and it is a dynamic influence line defined like:

$$A(L/\lambda)=\left|\frac{\cos\frac{\pi L}{\lambda}}{\left(\frac{2L}{\lambda}\right)^2-1}\right| \tag{5}$$

G (λ) depends on the so-called dynamic characteristic of the train and the damping coefficient (ξ) of the span structure. This parameter determines the range of the effect of the train and units are expressed in kN / m.

Knowing the spectral response, it is possible to determine the acceleration in the middle of the span for simple split beams for the critical speeds of the train.

$$G(\lambda)=Max\left[\frac{1}{\xi X_i}S_{0,i}(\lambda)\left(1-\exp\left(-2\pi\xi\frac{X_i}{\lambda}\right)\right)\right] \tag{6}$$

where X_i is the length of the train part, including the i-th number of axes.

It should be noted that using models of high-speed trains A1-A10 is justified in cases when at the time of designing of engineering structures the type of high-speed train is not defined. Thus, the envelope values constructed on the maximal values of the spectral characteristics of the A1-A10 trains for the whole range of excitation length (λ) exceed the corresponding values for real domestic and foreign high-speed trains (Figure 1). It means that in order to perform dynamic calculations it is sufficient to use only A1-A10 trains, and not all 22 trains regulated by [8].

Spectrum investigation of dynamic effects of European and domestic trains allows to conclude that the frequencies of the impact have a wide range of values. Thus, the design of engineering structures for all possible trains is irrationally and doesn't allow optimizing structures in order to minimize the dynamic impact and consequently the materials consumption. In this case the requirement to determine the list and characteristics of a high-speed train intended for operation in the design task is the main concern. The principle of universality of the high-speed line in this case goes against economic considerations, which certainly should be taken into account at the earliest stages of the project, in justifying the investment and determining the main goal of the HSR construction.

It should be noted that the parameters of the envelope of the A7-A10 models take into account the majority of real trains, while having a much smaller range of dynamic impact (Figure 2).

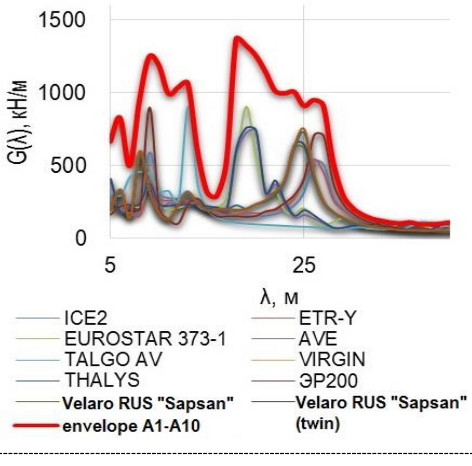

Figure 1. Compare of the spectral characteristics of real high-speed trains and the envelope for the A1 – A10 trains

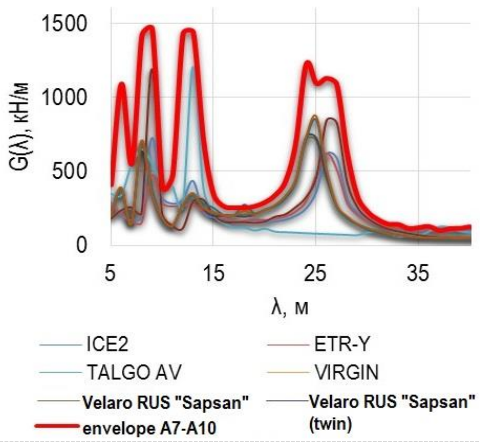

Figure 2. Compare of the spectral characteristics of real high-speed trains and the envelope for the and A7 – A10 trains

4. Development of recommendations of the appointment of a minimum mass of a span

Using the expression (3), there are set up the dependences defining the requirements of limiting the minimum mass of span by the condition that the permissible vertical accelerations of the span won't be exceeded for the ballast and ballastless track. As an example, the dependencies are constructed for span structures of prestressed reinforced concrete and steel (composite reinforced concrete) full length of 34.2 m along the envelopes from the A1-A10 and A7-A10 models (Figure 3-4). This construction is the main one in the design of artificial structures at the high-speed railway "Moscow-Kazan".

The abscissa of the graphs is λ, the excitation wavelength. In order to go to the speed, it is necessary to multiply the excitation wavelength by the value of the natural oscillation frequency:

$$V = \lambda \cdot f_1 \Rightarrow \lambda = \frac{V}{f_1} \tag{7}$$

The separation according to the types of construction in the presented dependences is caused by different values of the standardize damping coefficients for metal and reinforced concrete structures.

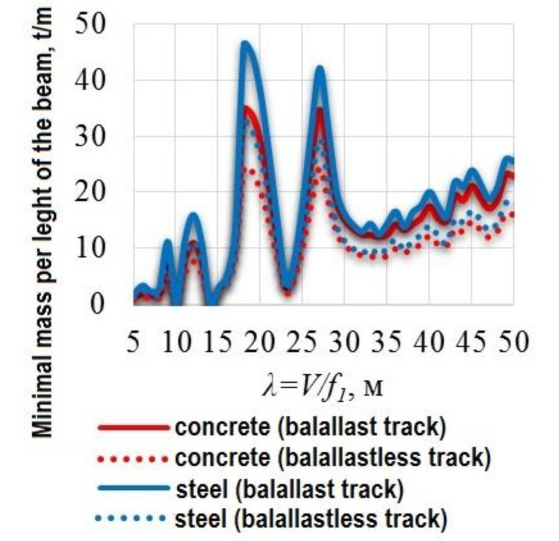

Figure 3. Recommendations for assignment of a minimum mass of a span for simple span structures of 34.2 m (calculated trains A1-A10)

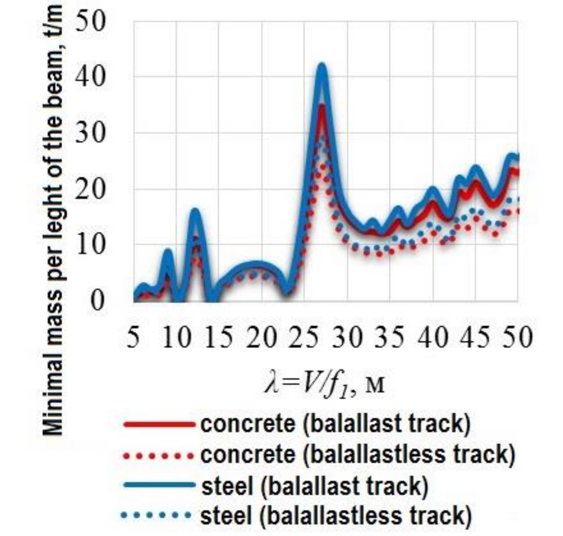

Figure 4. Recommendations for assignment of a minimum mass of a span for simple span structures of 34.2 m (calculated trains A7-A10)

On the basis of the above results, recommendations have been developed for limiting the lower limit of the natural frequencies of oscillations of cut beam girder structures (Figure 5, [19]). In contrast to the recommendations of the International Union of Railways (UIC), developed for speeds of less than 250 km / h and given in the Eurocode [20] (Figure 5), limitations of the lower limit of the natural frequencies of oscillations of span structures (10 to 30 m in length) allow at the initial design stage to assign the main design parameters in such a way as to minimize the dynamic impact of the mobile load at train speeds of up to 400 km / h.

It should also be noted that the use of a limited number of train models (for example, A7-A10) allows to significantly reduce the materials consumption of structures (in some cases up to 50%), reduce the permissible values of natural frequencies, which determine a significant economic effect in the construction the whole highway.

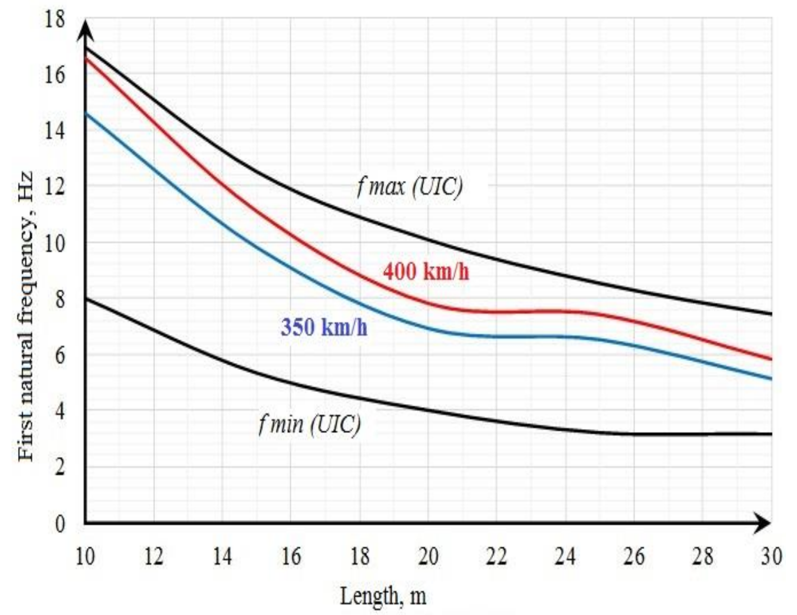

Figure 5. Recommendations for limiting the lower limit of the natural frequencies of oscillations of simple beam structures for train speeds of 350 and 400 km / h

5. Conclusion

As a result of the research using the analytical technique of dynamic calculation, the requirements for limiting the minimum mass of span of simple span system were obtained with the condition of limiting the permissible vertical accelerations of the span

During the research, recommendations were developed to limit the lower limit of the natural vibration frequencies of simple beam structures for train speeds of up to 400 km / h. The presented limitations of the lower limit of the natural frequencies of oscillations of span structures allow us to determine rational ranges of parameters of span structures taking into account the dynamic effects of the influence of high-speed load.

Consideration of recommendations on the assignment of a minimum mass of span structures and the limitation of the lower limit of the natural frequencies of oscillations of simple span structures significantly reduces labor costs for design and reduces the likelihood of possible adjustments after performing dynamic calculations.

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