Verification of the Finite Element Model of a Moving Load Passing Over a Single Irregular Suspended Load in the Dynamic Analysis of a Beam System

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ABSTRACT

This article compares the variants of dynamic models of mobile load to describe the joint oscillations of span structures and vehicles on road bridges, taking into account the irregularities of the road surface. Using a known solution to the beam system oscillation problem, when the sprung load moves through a single unevenness, the joint modeling application of an inert mobile load and a span structure in the LS-Dyna FE complex using contacts is considered. The proposed method eliminates the need to use special plugins to describe the car dynamics and allows considering the separation of the wheel from the road surface. At the same time, the use of contacts to create dynamic models of vehicles in the FEM is complicated by the lack of a verified way to account for road surface irregularities. In bridge calculations, spatial modeling of an elastic pavement layer with irregularities leads to the fact that the rigidity of the span structure varies in length depending on the micro profile. An effective way to solve this problem is to use solids with orthotropic material properties to describe the geometry of irregularities. Due to the unequal mechanical properties of the material along and across the beam, the layer with irregularities adequately transfers the load from the vehicle model to the supporting structures while not affecting the rigidity of the span structure. A good coincidence of the results of solving the dynamic problem by the proposed method in LS-Dyna with the results obtained by other authors in the SAP2000 program shows the possibility of using contacts for the dynamic calculation of bridge structures considering the irregularities of the road surface.

Keywords-finite element method; dynamic system; LS-Dyna; mobile load; road surface irregularities; contact algorithms

I. INTRODUCTION

The dynamic behavior of out-of-class and unique bridge structures regarding the passage of heavy vehicles is assessed during the design process in the way of a single side or in a column. The need for such calculations is due to the presence of heavy road trains moving at high speeds in the traffic flow on motorways. As a result of the dynamic calculation, significantly higher dynamic coefficients can be obtained, compared to those proposed in regulatory documents. A great contribution to the development of the theory of dynamic calculations of bridges for moving loads is made by scientific works carried out by employees of the Department of Structural Mechanics of the Voronezh Civil Engineering Institute (VISI, now VSTU). The theory of dynamic action of moving loads on various bridge structures, created by a group of Voronezh researchers, is presented in [1-4]. Today, this theory is actively developing and being adapted for use in modern finite element complexes [5-7].

In [5], a dynamic calculation taking into account the inertia of the moving load is performed using the finite element complex SAP2000, supplemented by a program in the Mathcad system to take into account feedback and roadway irregularities. This approach is of great practical importance, since it allows using the theory of random functions when describing the roadway profile.

The method of joint modeling of an inert moving load and a superstructure in LS-Dyna using element contact algorithms, considered in this paper, eliminates the need to use auxiliary programs to describe the dynamics of a vehicle. The module for determining the contact forces between elements in dynamics problems is implemented in a large number of modern finite element programs, which significantly simplifies its use for practical purposes. However, its use in calculating transport structures is complicated by the lack of recommendations for taking into account the unevenness of the road surface [7]. In [8], the method of joint modeling of a moving load and a superstructure is used to calculate a road bridge for the passage of a three-axle EQ3166 truck in LS-Dyna. In [9], a detailed model of a 40 ton truck is used to analyze the stress-strain state of a quickly erected pontoon bridge. Authors in [10] considered a method for joint modeling of vibrations of a moving simple load and a superstructure in the FE program Midas NFX using the built-in algorithm Contact-General. In [11-13], this method was developed further, where instead of a load, a simplified model of a two-axle passenger car with elastic and inelastic connections simulating the operation of the suspension was used. Authors in [14, 15] focused on the use of FEM to developed simulation of the Wheel Track Testing loading in order to predict the permanent deformation in conventional and rubberized asphalt mixes. Authors in [16-19] focused on FE modeling and techniques for moving loads and predict dynamic response of different structures. Over many years of research, various models of tire-road surface interaction have been developed, including using contact algorithms in FEM [6, 7]. The level of detail of the models varies from simple ones, in which the tire is considered as a spring damper system, to much more complex ones, in which volumetric finite elements are used to describe both the tire and the road surface [6, 7]. The considered FE tire models are designed to study the dynamic behavior of vehicles and improve the performance characteristics of the suspension. In such models, roadway deformations under wheel load are usually not taken into account. This simplification allows the use of "rigid" material to describe the upper layer of the road surface and the micro-profile, which significantly saves computing time.

In bridge calculations, spatial FE modeling of an elastic layer of a road surface with irregularities results in varying rigidity of the superstructure along the length depending on the micro-profile. In this paper, the use of spatial FE with orthotropic properties to describe the geometry of irregularities is proposed for the first time (Figure 1). Due to the unequal mechanical properties of the material along and across the beam, the layer with irregularities adequately transfers the load from the vehicle model to the supporting structures and does not affect the rigidity of the superstructure.

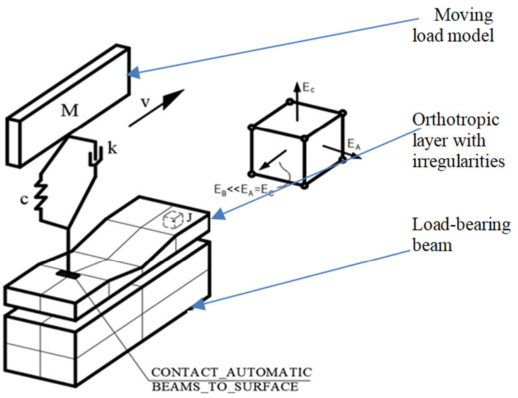

Fig. 1. Scheme of setting roughness and sprung load.

II. PROBLEM STATEMENT

To verify the proposed method for modeling road surface irregularities, the vibrations of the beam system during the movement of a sprung load were calculated in the LS-Dyna program. A well-known solution to this problem using the SAP2000 FE complex and the Mathcad computational program is described in [5]. Figure 2 shows the calculation scheme of the dynamic system.

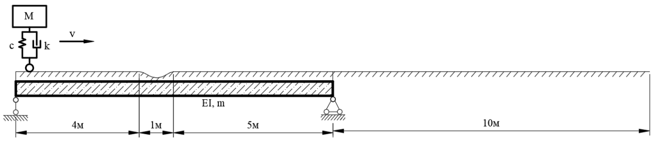

Fig. 2. Dynamic calculation scheme.

The beam cross-section has a square shape of 15×15 (cm). Reinforced concrete with an elastic modulus of E = 30,000 MPa, Poisson's ratio μ = 0.2, and bulk density γ = 24 kN/m^3 is selected as the beam material. Beam deformations due to their own weight are not taken into account. An uneven path with a single depression is given by:

$$\begin{cases} 0, \quad v \cdot t < \left(\dfrac{l}{2} - a\right); \\ \dfrac{h_0}{2}\left(1 - \cos\dfrac{2\pi \cdot t}{a}\right), \quad \left(\dfrac{l}{2} - a\right) \le v \cdot t < \left(\dfrac{l}{2} - a\right) = 0; \\ 0, \quad v \cdot t > \dfrac{l}{2} \end{cases} \qquad (1)$$

where a = 1 m – rough length, h_0 = 0.01 m – depression depth.

The following parameters of the moving sprung load were adopted in the calculation: mass m = 2000 N; elastic connection stiffness c = 150 kN/m; inelastic resistance coefficient k = 1 kN/(m/s); motion speed v = 5 m/s.

III. FINITE ELEMENT MODEL DESCRIPTION

Assignment of FE types, materials, sections, assignment of loads and boundary conditions was performed in the LS-Dyna program using keywords in the task text file. Each keyword contains a set of maps similar in purpose and containing information about the model. The keyword *NODE determines the location of nodes. The keyword *ELEMENT is responsible for creating finite elements. The description of materials and elements used in the FE model in LS-Dyna is given in Table 1.

TABLE I. DESCRIPTION OF ELEMENT TYPES AND MATERIAL MODELS

Object	Element	Element type (LS-DYNA)	Material model
Beam system	Beam	EQ.3: 8-node volume element with full integration scheme and 6 degrees of freedom per node	001-ELASTIC
	Road surface layer with a depression	EQ.3: 8-node volume element with full integration scheme and 6 degrees of freedom per node	002-MAT_ORTHOTROPIC_ELASTIC
Sprung load	Support part	EQ.1: Hughes-Liu Beam Element	020-RIGID
	Elastic connection	2-node 1D element	S01-SPRING_ELASTIC
	Damper	2-node 1D element	S02-DAMPER_VISCOUS
	Load	EQ.16: Shell with full integration scheme	020-RIGID

The interaction of the inert moving load and the supporting system utlized the element contact algorithm. The modeled structure was the continuous steel-reinforced concrete bridge across the Kalmius River along Ilyicha Avenue, Donetsk city (supports 4-5-6-7 with distances 33.84 + 37.6 + 33.84 m in Figure 3), was made. Figures 3–6 exhibit the developed spatial FE model of a steel-reinforced concrete span structure in LS-Dyna.

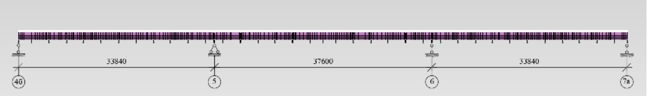

Fig. 3. Facade of the span structure.

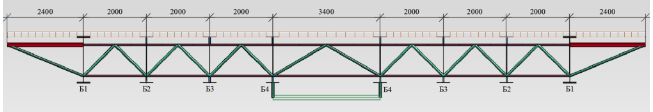

Fig. 4. Cross-section of the span structure.

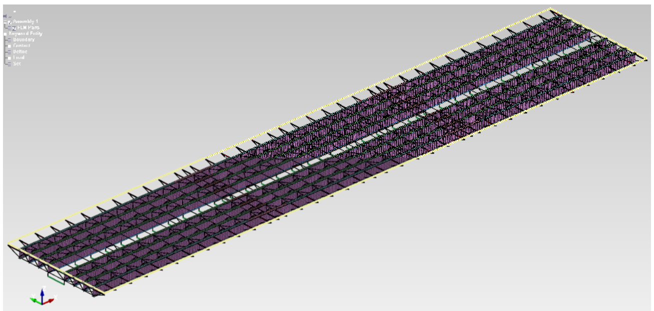

Fig. 5. Three-dimensional image of the FE model.

The road surface is specified with unevenness of 10 mm depth and 1 m length for every 10 m. The calculation is performed for the passage of a column of three-axle trucks following one another, each weighing 30.0 tf, at a speed of 60 km/h.

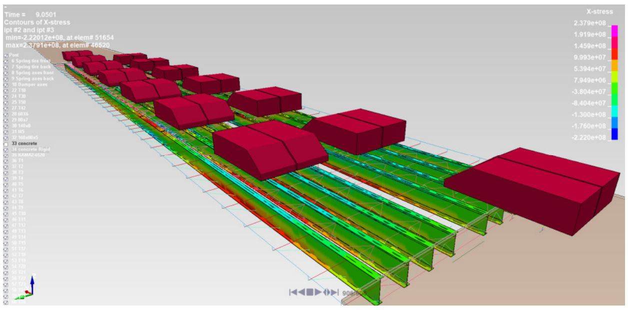

Fig. 6. Dynamic X-stress on the main beams.

According to the results of the static calculation along the influence lines, given in the explanatory note to the project, the maximum stress in the main beams (taking into account the dynamic coefficient) was 209.9 MPa. The highest normal stress in the chords of the main beams during the dynamic calculation in LS-Dyna was 237.9 MPa.

The translational movement of the load along the beam is specified by a linear function in PRESCRIBED-MOTION-RIGID. This option allows determining the motion parameters (speed, acceleration, or displacement) for the body nodes in the selected direction at each moment in time. A similar algorithm was used to calculate buildings and structures for seismic impact using specified accelerograms. During the first second of the calculation, a gravitational load is applied to the sprung mass. After the free oscillations have died down, the load moves at a constant speed.

The AUTOMATIC-BEAMS-TO-SURFACE algorithm is used to model the interaction of the support element of the moving load and the beam. It has high stability in problems where one of the bodies moves significantly in relation to the other. At each step of the dynamic calculation, the 1 cm long support beam element of the moving load is checked for penetration into the pavement layer with a depression. If penetration occurs, a force proportional to the penetration depth is applied to the support node and to the beam. The length of the support element is selected in order to ensure point support on the load-bearing system. A fragment of the finite element model with a moving load is shown in Figure 7.

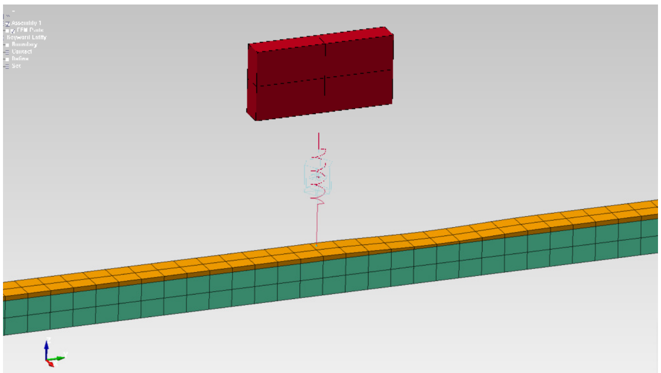

Fig. 7. Finite element model of a dynamic system.

The damping of the system is taken proportionally to the mass matrix and is specified by the keyword *DAMPING-GLOBAL in fractions of the critical value. The coefficient of structural damping $D_s = 1.0$ corresponds to approximately 3% damping of the fundamental frequency of beam oscillations ω_1=14.96 rad/s.

From the results, it can be seen that the calculation of the joint vibrations of the FE model was performed using the explicit method of central differences in LS-Dyna with a constant time step of Δt = 1.78×10^{-6} s. Figure 8 shows the deflections in the middle section of the beam, and Figure 9 shows the change in dynamic pressure. The solid red line shows the solution obtained in the LS-Dyna, and the dashed blue line shows the calculation results in the SAP 2000 package, given in [5]. The very close coincidence of the results should be noted. The results of LS-Dyna modeling of beam vibrations when a sprung load passes over a single unevenness show a solution very close to the known solution of this problem. Since the calculation takes into account the effect of feedback, and also allows for the possibility of a wheel being torn off the surface, the algorithm can also be used to assess the vibration level of high-speed train and automobile crews. Figure 10 shows graphs of vertical displacements of the sprung mass and the support unit of the moving load model.

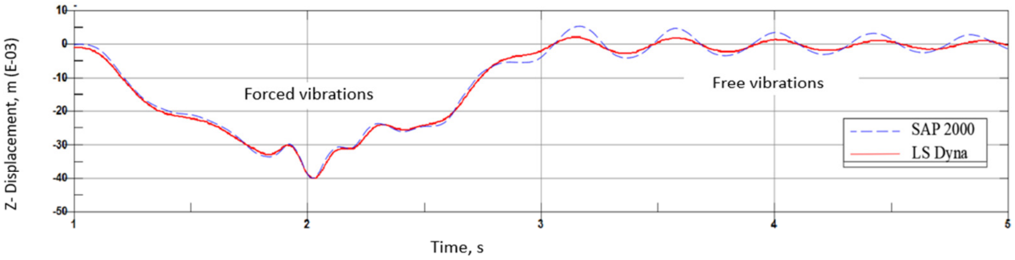

Fig. 8. Beam deflection in the middle of the span.

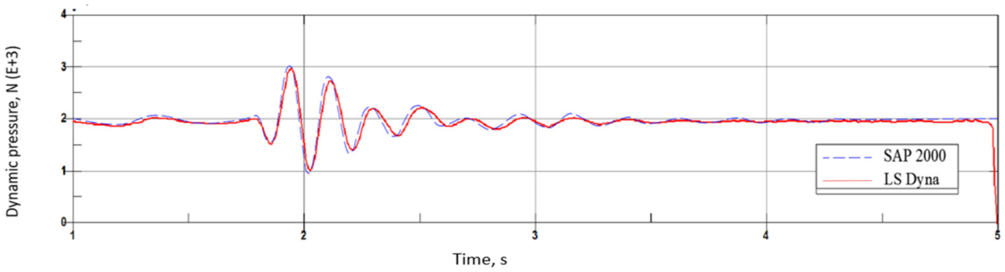

Fig. 9. Dynamic pressure of the sprung load.

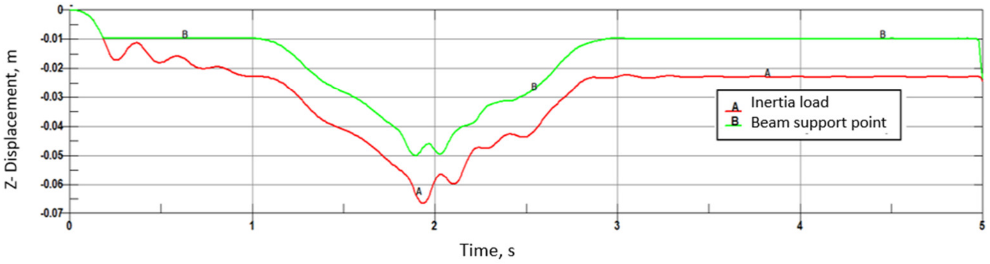

Fig. 10. Vertical displacements of the elements of the sprung load.

IV. CONCLUSIONS

The performed comparative dynamic calculations of beam system vibrations when the simple model of a moving load passes through a single unevenness in LS-Dyna allow us to draw the following conclusions:

- The verification of the proposed method for modeling unevenness in the joint calculation of a moving load and a supporting system shows the possibility of its application for the dynamic calculation of bridge structures.
- Modeling the interaction of an inert moving load and a supporting system using the element contact algorithm allows us to perform the calculation without using auxiliary programs to describe the dynamics of the vehicle, as well as to take into account the separation of the wheel from the surface.
- A promising direction for the development of the proposed calculation method is to take into account the unevenness specified by a random distribution function, and to test the algorithm for more complex vehicle models.

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