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BRIDGES WITH ADAPTIVE RAILWAY TRACK

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The concept of an adaptive railway track, consisting of sleepers initially elevated (with the curvature tailored according to the detected, coming train) and then yielding in a controlled way under the moving vehicle is discussed. The problem formulated as a shape control requiring the minimum integral measure of the track deflection gives, as a side effect, a significant reduction of the corresponding integral measure of the dynamic contact forces between the track and wheels.

Key words: adaptive bridges, shape control, dynamic analysis

1. Introduction

It is well known that the vibration process caused when trains cross over a bridge consists of:

- a deterministic component caused by the deflection of the bridge
- a random component caused by existing track level defects.

Neglecting the second component caused by disturbances of the track shape and normally absorbed by the suspension of the rail-car, let us concentrate on the first one. Low frequency disturbing factors are present due to deflection of the bridge span and those of high frequency are present due to an angle of rotation of the span on the support. Both factors depend mainly on the train speed, load distribution, the bridge characteristics and the stiffness of the suspension of the vehicle.

Usually, designers are concentrated on active and adaptive suspensions of vehicles to reduce excitation caused by disturbances in smoothness of railway tracks (Jézéquel et al., 1993; Jézéquel and Roberti, 1991; Knolle, 1997).

Another area of the research activity is protecting the structure in a controlled way from earthquakes and undesired vibrations using active tendons and smart bearings (Meirovitch, 1990; Parducci and Mezzi, 1992). However, the problem of crossing a flexible bridge span on a track is different and knowledge of mechanical model behaviour on the entire structure can improve significantly the effectiveness of the applied adaptation process. This technical problem is recognised and formulated as a fully actively controlled gap (between the vehicle and guideway) in "magnetic levitation" (MAGLEV) train (Ellmann, 1997; Knolle, 1997). Contrary, our proposition to apply the adaptive track concept to conventional railway infrastructure is mostly based on a semi-active control process, without the need for substantial external energy sources to move smart sleepers up and down. Similar problem was analysed, however in a fully actively controlled formulation in Bogacz (1996).

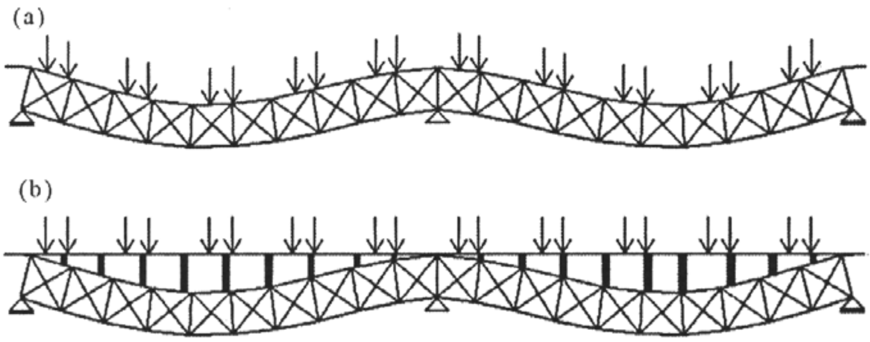

Fig. 1. Concept of active track; (a) conventional track, (b) active track

The proposed concept of the active track support can be explained with the help of Fig. 1. Prefabricated smart sleepers (Fig. 2a) will be equipped with actuators (Fig. 2b) able to shift the track up and down, and will be mounted to the bridge superstructure in a conventional way. Therefore, only vertical movements of the supports will be controlled while other components of mutual movements will be eliminated.

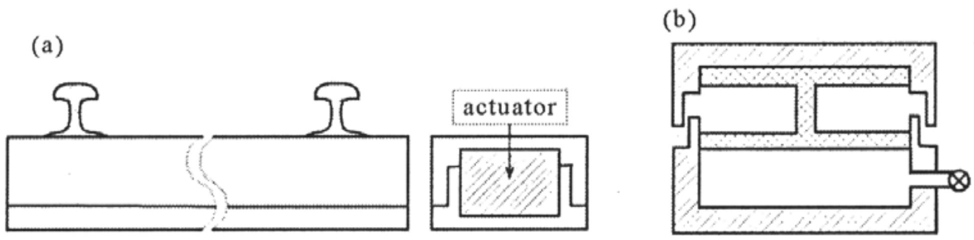

Fig. 2. (a) Smart sleeper, (b) actuator

The complete active support system would be equipped with: smart sleepers, sensor system identifying the passing train and measuring track deflections and a controller realising in real time the control strategy of the track deflection. However, much cheaper, and more realistic in conventional applications is an adaptive concept allowing only vertical adaptation of sleepers under a moving load (semi-active control). Generation of an initial track curvature, which is pre-calculated and selected after identification of the approaching train, can be done in advance on an unloaded track, in this way, only a limited amount of energy is required and the system becomes more feasible and reliable. Then, under the moving load, the pre-computed strategy through valves opening in actuators is applied and thus an optimal track adaptation, which minimises the overall track deformation and furthermore the dynamic contact force between track wheels, can be reached. The identification zones (see Fig. 4) will be placed about 2 km before the entry of the bridge where velocity and mass distribution of the train will be estimated. Additionally, as the side effect, the following associated features can be simultaneously estimated:

- Decrease of the overall dynamic load
- Increase of the train safe speed limit
- Extension of the structure life time
- Increase of passenger's comfort and safety
- Reduction of the material fatigue effect.

Application of smart sleepers requires a system of:

- train identification (speed and load distribution) such as proposed by Kalický and Vlk (1996) (see Fig. 3)
- control unit deciding upon an application of the pre-computed strategies of the sleeper adaptation
- the system of controllable valves in the smart sleepers.

2. Problem formulation

The objective is to apply the track shape control (by means of active smart sleepers with height controlled under train load), minimising the track deflection measure $\|\boldsymbol{u}(\boldsymbol{p},\boldsymbol{u}^0)+\boldsymbol{u}^0\|$ (where $\boldsymbol{u}$ denotes the resultant track deflection dependent on the load $\boldsymbol{p}$ by the passing train and the applied sleepers shifting

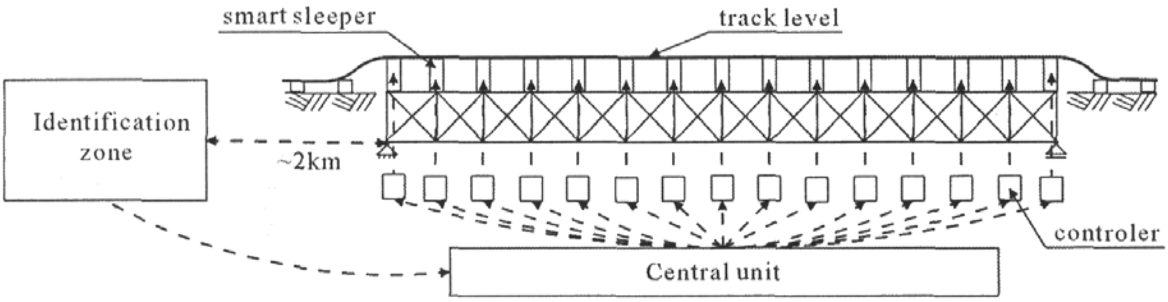

Fig. 3. Control and measurement concept

$\boldsymbol{u}^0$), as the response for disturbing factors (low and high frequency factors). The associated effect of a significant reduction of the corresponding measure of dynamic load increment (the total reaction for all disturbing factors) is expected. The following options of the active track task formulation can be considered:

1. Passive sleepers, with the applied sleepers shifting $\boldsymbol{u}^0 = \text{const}$, fixed for a particular bridge and an expected set of passing trains
2. Passively adaptive sleepers, with $\boldsymbol{u}^0 = \text{const}$, for a specified bridge and tailored for the identified particular train
3. Adaptive sleepers designed for a particular train and adapting vertically in the controlled way with $\boldsymbol{u}^0 = \boldsymbol{u}^0(t)$, $d\boldsymbol{u}^0(t)/dt \leqslant \mathbf{0}$
4. Fully actively controlled sleepers (including shifting up of loaded track) with $\boldsymbol{u}^0 = \boldsymbol{u}^0(t)$.

The cost of application increases from case 1 to case 4, where the last case shows the ultimate effect of the actively controlled support resulting in an ideal, undeformed ($\boldsymbol{u}^0(t) = -\boldsymbol{u}(t)$) track line. Case 1 requires only passive rectification of the track and therefore is the cheapest solution, with the minimal cost of application. Case 3 with economic constraint

$$\frac{d\boldsymbol{u}^0(t)}{dt} \leqslant \mathbf{0} \tag{2.1}$$

is naturally considered as a realistic desired control in application to passively adaptive sleepers, of old, unballasted bridges and especially of historical steel bridges (usually quite flexible but demanding retrofitting without modifications of the bridge structure itself).

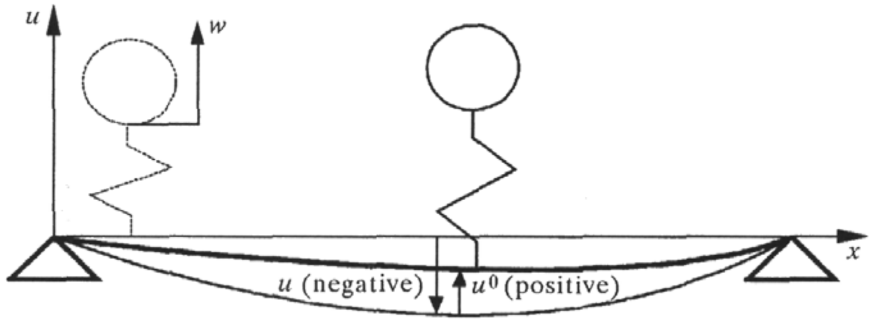

Fig. 4. Definition of $\boldsymbol{u}$, $\boldsymbol{w}$, and $\boldsymbol{u}^0$

Case 4 leads to the desired control into a fully active shape control of guideways for transrapid MAGLEV trains (eg. considered by Thyssen Transrapid System GmbH, see Ellmann (1997)). As the magnetic field is generated continuously in MAGLEV applications, the constraint of the dissipative character of shape modifications $d\boldsymbol{u}^0(t)/dt \leqslant \mathbf{0}$ is not so critical in this case. The closed loop control proposed in Ellmann (1997) applies radar measurements of the gap between the guideway and the chassis. Contrary, in our proposition, the control loop can be open, due to pre-computed strategies of sleepers movements.

A global, however simplified, dynamic model of the train-bridge contact problem has been applied (Fig. 4). This model contains:

- the model of an elastic bridge behaviour
- the model of a passing train composed of concentrated masses suspended on elastic springs
- the controlled gap $\boldsymbol{u}^0(t)$ (realised through the smart sleepers) between the track and the bridge structure itself.

The resultant response of the system for the train loading and the active support actions contains the track (end of the entire bridge structure) deflection function $\boldsymbol{u}(\boldsymbol{p}, \boldsymbol{u}^0)$ and the dynamic increment of the contact force (between the rail vehicle and the track) $\boldsymbol{S}(\boldsymbol{p}, \boldsymbol{u}^0)$. The dynamic equilibrium equation of the system is the following one

$$\mathbf{M}\ddot{\boldsymbol{u}}(t) + m\ddot{\boldsymbol{w}}(t) + \mathbf{C}\dot{\boldsymbol{u}}(t) + \mathbf{K}\boldsymbol{u}(t) = \boldsymbol{S}(t) + \boldsymbol{Q} \tag{2.2}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are mass, damping and stiffness matrices of the structure, respectively, $\boldsymbol{u}(t)$ is the vector of unknown nodal displacements (only vertical components of track deflection are considered in the formula for

$\boldsymbol{S}(t) = k[\boldsymbol{w}(t) - \boldsymbol{u}(t) - \boldsymbol{u}^0(t)])$ and $\boldsymbol{Q}(t) = -m\boldsymbol{g}$ in the vector of external gravity forces coming from moving masses and applied to the bridge structure. On the other hand, m denotes the moving mass distribution, $\boldsymbol{w}(t)$ denotes the corresponding vertical movements, k denotes the stiffness coefficients of the suspension springs and all these components are applicable in the equilibrium equations (only in the vertical direction) for the nodal points of the span upper deck. It is assumed that the structural dynamic behaviour can be modelled with sufficient accuracy with 2D model of the system. Numerical implementation of the damping matrix has been chosen as the Rayleigh formula with α and β factors indicating external and internal damping in the structure

$$\mathsf{C} = \alpha\mathsf{M} + \beta\mathsf{K} \tag{2.3}$$

The Newmark integration approach, as described in Bathe (1996), has been applied splitting (2.2) into two equations (see in Flont and Holnicki-Szulc, 1997) solved iteratively to get desired accuracy.

The objective function of the active control requires minimisation of the following integral measure of resultant track deflection (2.4) (restricted only to the loaded nodes) where Δx and Δt denote the discretisation in space and time, respectively

$$\min \|\boldsymbol{u}(\boldsymbol{p}, \boldsymbol{u}^0) + \boldsymbol{u}^0\| = \min \Sigma_x \Big(\Sigma_t |u(p, u^0) + u^0| \Delta t \Big) \Delta x \tag{2.4}$$

The control function $u^0(t)$ is constrained with respect to the chosen control strategy (2.1) $\div$ (2.4) and the following optimisation procedures are applied: QLD (Schittkowski, 1984) and S-Sleeper (Flont and Holnicki-Szulc, 1997). The associated effect of the corresponding decrease of the measure of dynamic load increment (2.5) can be observed

$$\|S\| = \Sigma_t |S_t| \Delta t \tag{2.5}$$

3. Heuristic procedure for desired control

The QLD procedure is time consuming and the memory requirement increases significantly together with the length of the train. A heuristic procedure (named S-SLEEPER) described bellow, has been proposed as the competitive solver for the optimal design of the actively controlled gap $\boldsymbol{u}^0$ problem. The additional advantage of this numerically efficient procedure is easy access to introduction of additional, technical constrains imposed on the desired control process. The mentioned above constraints (e.g. limits for speed of actuator movement) can be expected as output from experimental tests.

The idea of the S-SLEEPER procedure is based on the character of a particular node behaviour during the passage of the train (Fig. 2). If the objective function of the active control requires minimisation of measure (2.4) of the resultant track deflection (in the discretized model) the following iterative process can be proposed for $i = 1, 2, \dots$

$$\min \Sigma_{it} \frac{1}{lt} \Big\{ \frac{1}{lx} [\Sigma_{ix}(u(p, u^0_{i-1}) + \Delta u^0_i)] \Big\} \tag{3.1}$$

where $u^0_i = u^0_{i-1} + \Delta u^0_i$ and u^0_0 is determined from the condition $u^0_1 = -u(p, u^0_0)$ of the "ideal" track dynamic response requiring $\boldsymbol{S} = \mathbf{0}$ and $\boldsymbol{w} = \mathbf{0}$.

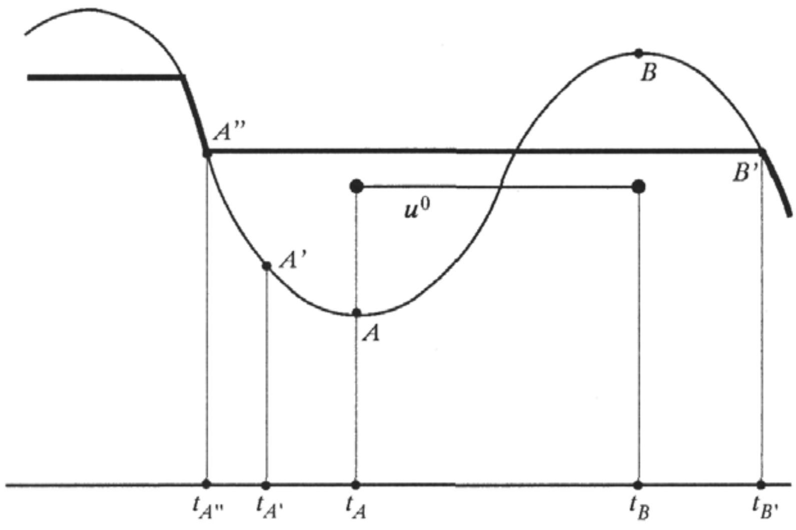

Fig. 5. Heuristic strategy of S-Sleepers control

As a matter of fact, the first iteration solves case 4 but requires action of the sleepers in lifting the loaded track. Constraining farther consideration to adaptive case 3, when the desired control u^0 has to be a monotonically non-increasing function, a strategy of solution (3.1) modification is proposed. To do that, let us consider the desired control $\overline{u}^0$ determined in the above iterative process for a chosen sleeper (Fig. 5). In order to satisfy the above constraints let us now search for a modified desired control function u^0 as close to $\overline{u}^0$ as possible

$$\min f = \min \frac{\Delta t}{l_t} \sum_{it=1}^{n} (u^0_i - \overline{u}^0_i)^2 \tag{3.2}$$

and satisfying the constraint $du^0(t)/dt \leqslant 0$.

The first and the second derivative of objective function (3.2) with respect to u_i^0 is the following

$$\frac{df}{du_i^0} = \frac{2\Delta t}{l_t} \sum_{it} (u_i^0 - \overline{u}_i^0) \qquad\qquad \frac{d^2 f}{d(u_i^0)^2} = \frac{-2t}{l_t} \tag{3.3}$$

As the second derivative is possitive, the necessary and sufficient condition for the minimum of the unconstrained objective function is vanishing of the first derivative, which leads to $u_i^0 \equiv \overline{u}_i^0$ (solution to control case 4). In control case 3, however, we can expect a piece-wise constant solution in intervals where the function $\overline{u}_0$ is increasing, due to active constraint (2.1).

If the constraint $u_i^0 =$ const is imposed (cases 1 and 2) the constant value of the sleepers elevation equal to the following arithmetical average value (3.4) is expected as the optimal solution

$$u_i^0 \equiv \left[\overline{u}_i^0\right] = \frac{1}{l_t} \sum_{it=1}^{n} u_i^0 \tag{3.4}$$

Let us now consider the following heuristic algorithm for determination of the desired control u^0 in case 3. If a local minimum of the function $\overline{u}^0$ is detected (point A in Fig. 5), then:

1. Search for the first local maximum (point B) coming after the time t_A
2. Determine average value (3.9) for the function $\overline{u}^0$ in the interval $\langle t_A, t_B \rangle$
3. Move the interval limit t_A to the left until the average value $[\overline{u}^0]$ measured on the interval $\langle t_{A'}, t_B \rangle$ is equal to $\overline{u}^0(t_{A'})$
4. Move the interval limit t_B to the right (and then, if necessary, the limit interval $t_{A'}$ to the left) until the average value $[\overline{u}^0]$ measured on the interval $\langle t_{A''}, t_{B'} \rangle$ is equal to $\overline{u}^0(t_{A''}) = \overline{u}^0(t_{B'})$
5. Check the previous elevation level. If the current is less than or equal to the previous level, then search the next local minimum. Else, take those two intervals and calculate the elevation level as the average over these intervals.

4. Simulation of active track support effects

4.1. One-span bridge example

The truss model of the bridge presented in Fig. 6 has been analysed. The cross-sections of all steel members were assumed to be $0.008\,\text{m}^2$. The calculated eigenvalues of the model were used to obtain critical velocities of the train inducing a structural resonance for moving constant forces ($\widetilde{v}_i = f_i\, d$, where $\widetilde{v}_i$ is the train speed, f_i natural frequency of the bridge, d indicates the distance between successive nodes of the upper deck) (Calçada and Delgado, 1995). The smallest eigenfrequency (11.2 Hz) corresponds to $\widetilde{v}_1 = 242\,\mathrm{km/h}$ (for $S \equiv 0$ or non-inertial loading) and $v_1 = 257\,\mathrm{km/h}$ (for $k = 1205\,\mathrm{kN}$ and $m = 24\,\mathrm{t}$). Sensitivity analysis shows that a small change (5%) in the suspension stiffness or the moving mass weight have very little influence on the critical velocities ($\sim 0.075\%$ and $\sim 0.037\%$, respectivly).

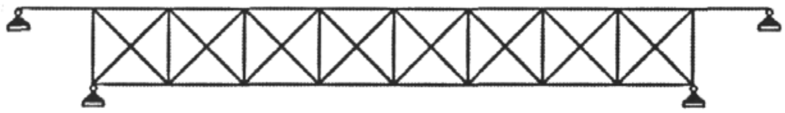

Fig. 6. One-span model

The dynamic increment of the contact force distribution for the uncontrolled one-span bridge model loaded by one mass moving with the speed v_1 is shown in Fig. 8. The reduction of the contact force during the first phase of the passage and increase of this force during the second phase can be observed. The corresponding deflection under the moving mass is shown in Fig. 7.

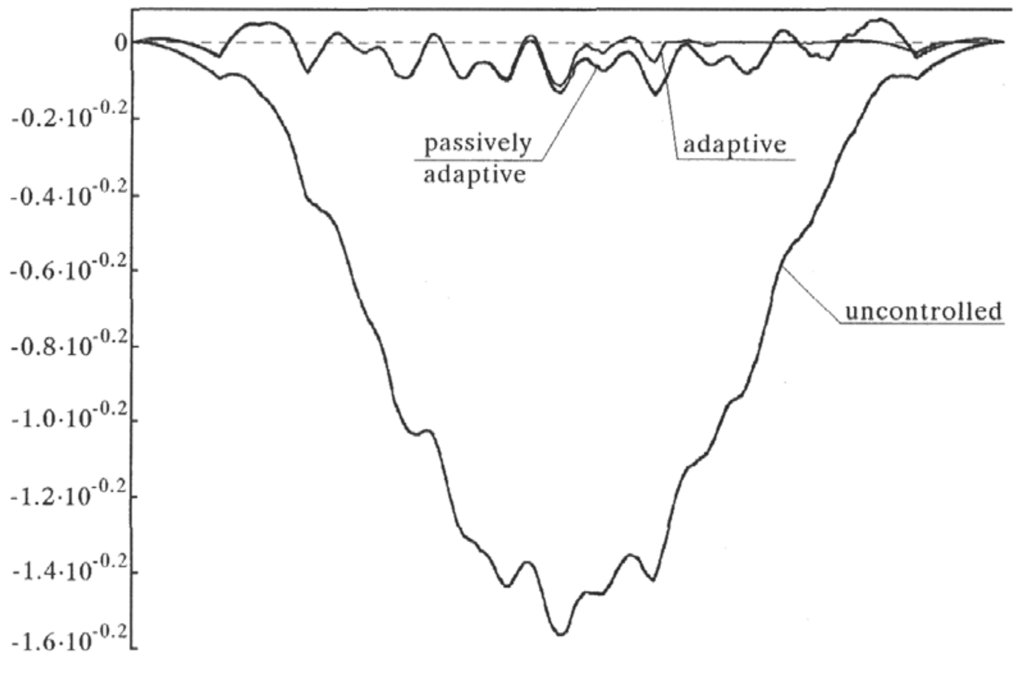

Fig. 7. Nodes displacement under moving mass (single mass case)

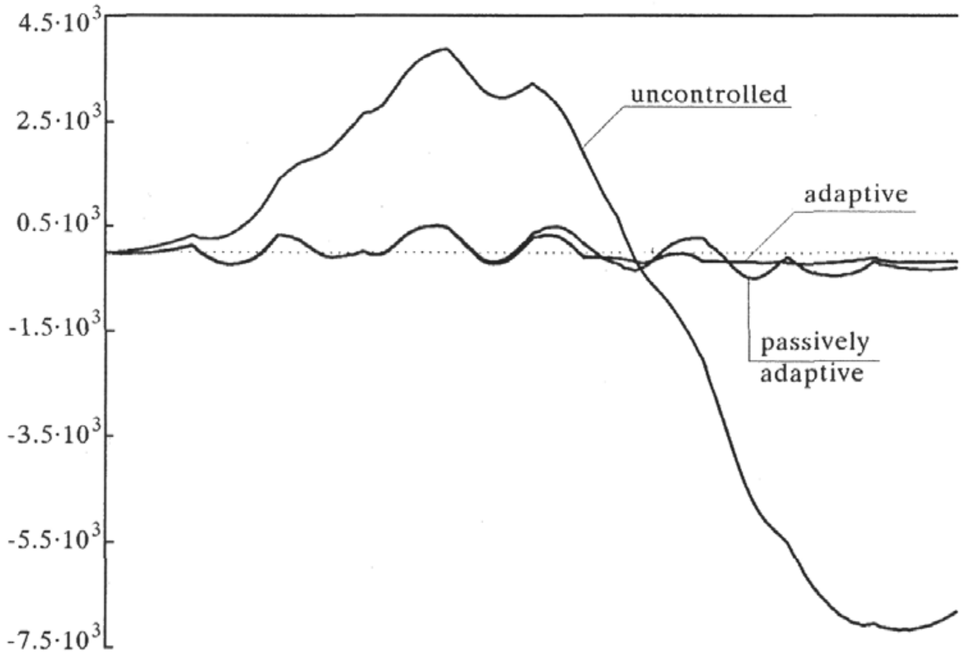

Fig. 8. Dynamic increment of the contact force (single mass case)

The results obtained for two control strategies (passively adaptive and adaptive control) are similar and prove thei efficiency (Fig. 7 and Fig. 8). Of course, for several moving masses the effect of the active track control has to be smaller.

4.2. Two-span bridge example

The next numerical example demonstrates influence of the length of chain of moving masses and its velocity on the reduction of the overall deflection and the contact force measures ((2.4) and (2.5), respectively). Taking into account the two-span bridge model shown in Fig. 9, the corresponding active control effects for the case of Passively Adaptive and Adaptive cases are shown in Fig. 10 ÷ Fig. 13, respectively. On the vertical axis the objective function ((2.4) and (2.5)) measures are exposed while on the horizontal ones the train velocity and its length (the ratio of the train length to the length of the bridge span) are shown.

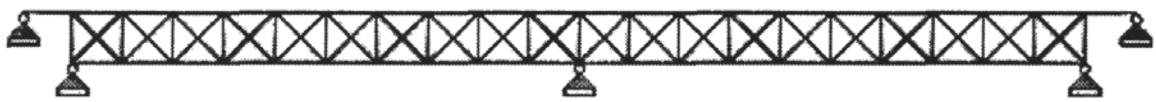

Fig. 9. Two-span bridge

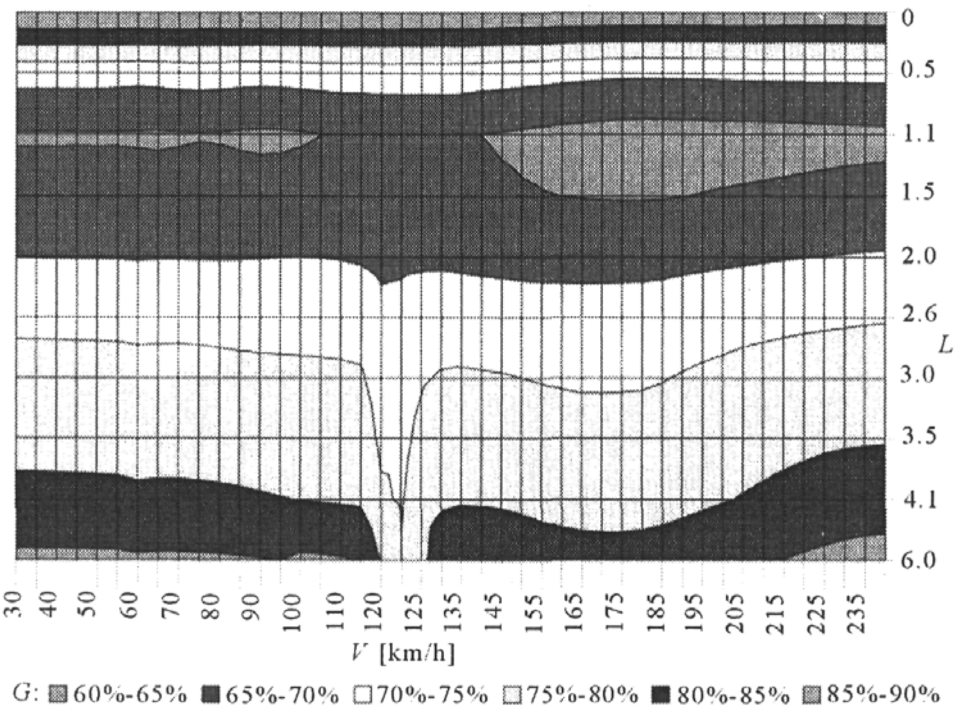

Fig. 10. Gains on track displacement – Passively Adaptive Case

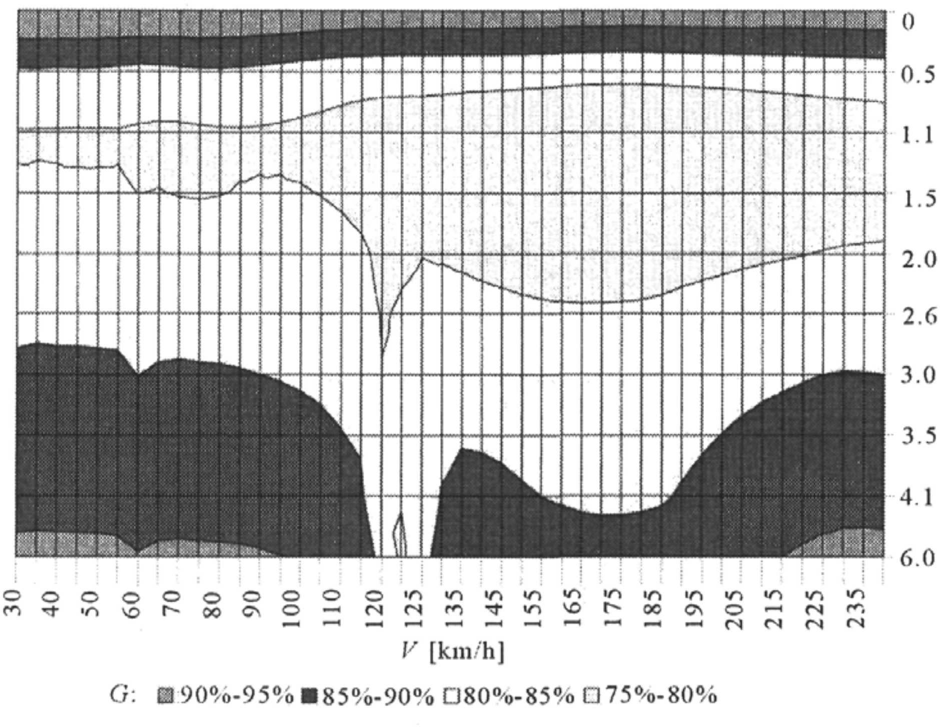

Fig. 11. Gains on track displacement – Adaptive Case

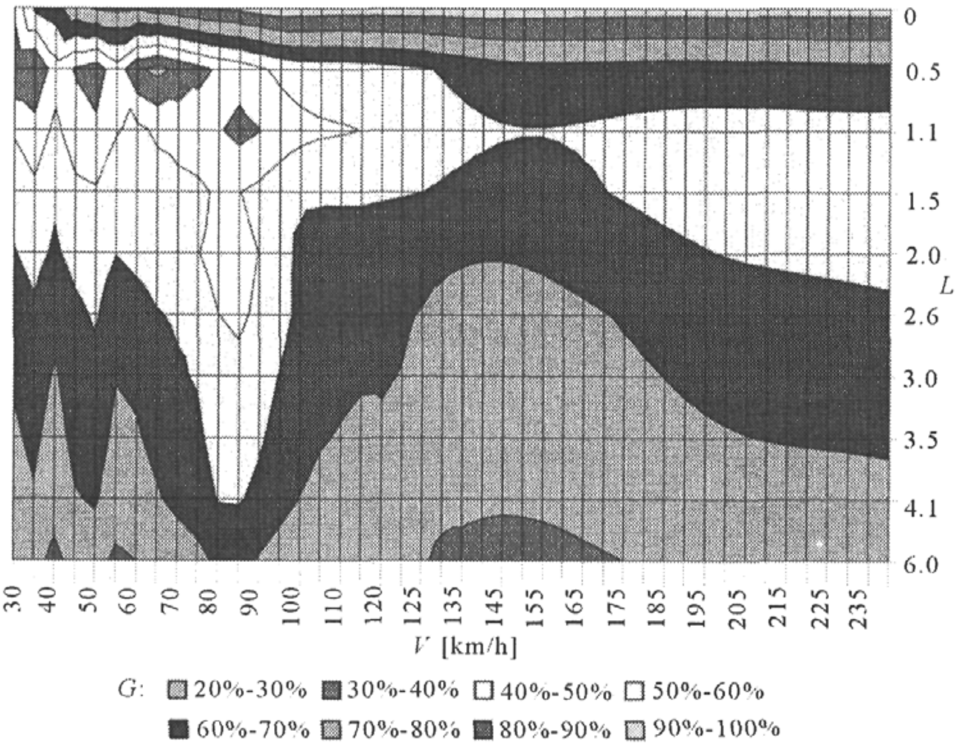

Fig. 12. Gains on dynamic load increment – Passively Adaptive Case

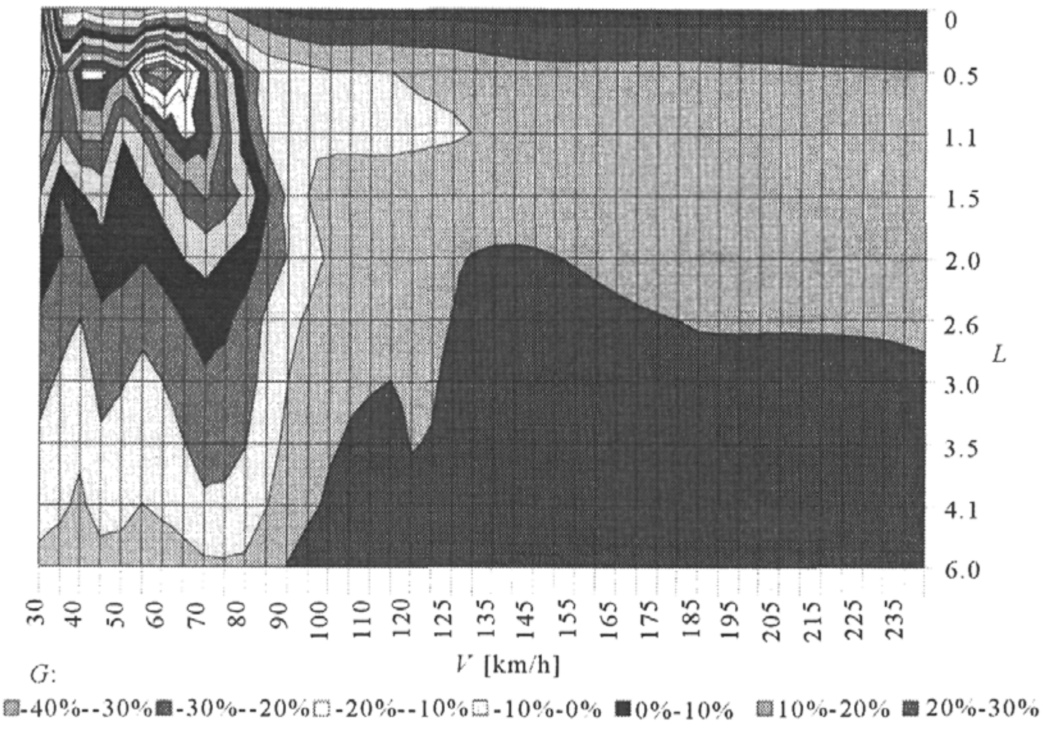

Fig. 13. Gains on dynamic load increment – Adaptive Case

As we can see, the active shape control of the railway track has significant influence on reduction of the overall measure of the dynamic increment of the control force, especially for the adaptive case.

An exceptional case corresponds to low velocities and the length of the train equal to the half span distance (Fig. 13), when reduction of the overall displacement measure causes an increment in the contact force measure. This phenomenon corresponds to the train velocity approaching critical values equal to $v_1/2$ and $v_1/4$, and a crude numerical model of the dynamic train-bridge system applied to computations.

4.3. Estimated simulation for the Forth Bridge

Retrofitting of old historical bridges (e.g. the Forth Bridge in Scotland (Fig. 14) analysed below as a case study) is one of the possible applications of the adaptive track concept. The cost of installation is justified in that case, as the main objective of such retrofitting is adaptation of the structure to the nowadays needs (increased train loading and speed) preserving the original structure unchanged as far as possible.

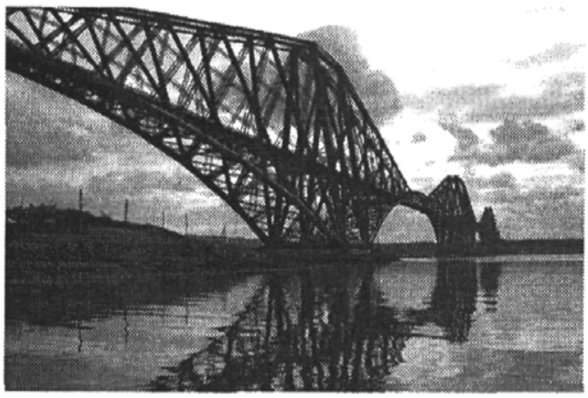

Fig. 14. The Forth Bridge

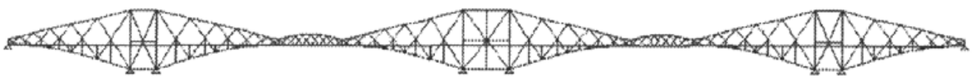

Fig. 15. The Forth Bridge – numerical model

Since there are some limits imposed on velocities and transport intensity, a freight train consisting of two engines in front with 20 waggons followed by another engine, was taken into calculations to estimate how much the concept could improve present problems. The train set was chosen as the bridge was designed and verified for. In addition, the upper limit of admissible velocity was chosen. Assuming the truss model of the bridge (see Fig. 15) the passively-adaptive case has been solved and 44.6% of the gain on deflection measure (2.4) and 40.7% of the gain on dynamic increment (2.5) have been obtained. The adaptive case has been calculated to compare the strategies and gains. The results were 45.5% and 41.8% for the deflection and dynamic increment measure, respectively. Taking advantage of the smart sleeper concept it can be achieved 20.4% and 20.7% of the gain for the allowable displacement even for such an unfortunate vehicle. Considering the strength of the structure, the maximal value of the occurring dynamic increment of the contact force between the wheels and rail can be lessened by 45.0% and 46.8% for passively-adaptive and adaptive control strategy, respectively.

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Mosty z samo-adaptującym się torem kolejowym

Streszczenie

Omówiona koncepcja samo-adaptującego się toru kolejowego opiera się na zastosowaniu inteligentnych podkładów. Podkłady, których wysokość może być zmieniana dzięki wyposażeniu ich w siłowniki, zastępują podkłady (mostownice) na moście.

Idea adaptacyjnego toru polega na wstępnym uniesieniu toru, którego krzywizna dopasowana jest do zidentyfikowanego, nadjeżdżającego pociągu i następnie w kontrolowany sposób opuszczaniu pod przejeżdżającym pociągiem.

Zadanie zostało sformułowane jako sterowanie kształtem toru przy założeniu minimalizacji całkowej miary uogólnionego przemieszczenia toru. Jako efekt uboczny można spodziewać się znacznej redukcji skojarzonej całkowej miary dynamicznego przyrostu obciążenia powstającego pomiędzy torem a kołami pociągu.

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