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Semi-Active Control of Track Subjected to an Inertial Moving Load

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Abstract

The paper deals with the problem of stabilization of vibrations of the load carrying structure via adaptive damping performed with a smart material. The properties of such a material must ensure reduction of vibrations, especially accelerations and displacements of selected stationary or follower points in a higher range than in the case of the material with homogeneous bilateral characteristics. Analytical calculations and numerical simulations proved the efficiency of the approach. Results obtained with the testing system equipped with magnetorheological controlled dampers will allow us to prove experimentally assumed control strategies and rheological properties of the filling material.

Keywords: control, moving inertial load, vibrations, smart materials

1. Introduction

Historic buildings and buildings founded on grades are particularly vulnerable to vibrations. Historic brick buildings are fragile, very susceptible to deformation. The low susceptibility of the material, which does not succumb to excessive momentary or long-term deformation is the main reason of damages. The negative impact of infrastructure on the surrounding buildings, particularly historic, forces us to take action to reduce the adverse external effects. In this aim, we assume the concept of modification of the track structure, to enable influencing its dynamic properties.

Pioneering concepts of integration semi-active control systems with engineering design, transportation and robotics date back several decades. Systems based on semi-active electro or magnetorheological dampers are an attractive alternative to passive and active systems. Correctly designed algorithms for semi-active control systems produce better results than the passive ones. The low power requirements are a strong competitive with active control systems. Over the years, semi-active systems are replacing passive and active systems. This is thanks to the emergence of more and more interesting design solutions of semi-active vibration absorbers. Today, not only rheological fluids, but also significantly cheaper air foam can be used as a medium of such absorbers. Wealth of properties of actuator opens up new possibilities in the design of control algorithms. Problems associated with optimal control methods of semi-active systems are still open. Mainly due to their nonlinear (bilinear) characteristics.

One of the first concept of semi-active control in mechanical systems was proposed by Karnopp, Crosby and Harwood [1]. In their work they presented the idea of active suppression of the oscillator with one degree of freedom, moving over uneven ground. Damping coefficient was a decision parameter. Solutions developed by the Skyhook algorithm is today one of the most widely used in active suspension control systems for vehicles. The idea was designed to improve comfort of passengers. Giraldo and Dyke [2], and Chen, Tan, Bergman, Tsao [3], showed that Skyhook method also gives good results for the oscillator moving over the simply supported continuum. Semi-active systems have also found numerous applications in structures subjected to seismic excitation. We should mention here works, e.g. Soong [4], and Yoshida, Fujio [5]. The task for semi-active control system was to stabilize the system when lost the equilibrium state.

The paper deals with the concept and the preliminary development of optimal control strategy of a track. Practical verification of received control algorithms requires dynamic measurements on the test stand. The description of the test stand has been done.

2. Optimization of the semi-active track

In this section we present in brief the methodology for solving optimal control problem for the semi-active track. For more details see [6].

The governing equation for the track system is given as follows

$$\dot{x} = Ax + \sum_{i=1}^{m} u_i B_i x + F(x), \quad x(0) = x_0 \ . \tag{1}$$

Here x, u stand for the state vector (composed of vertical displacements and velocities) and the input vector (composed of damping coefficients), respectively. The impact of a moving load on the system is described by $F(x)$. Matrices A and B_i result from both the method of discretization and dampers placement. In (1) the decision parameters u_i are given in nonlinear (bilinear) terms and therefore, none of the standard optimal control method, that leads to close loop solution (for instance LQR), can be here applied. In this project, at first we use the gradient methods to obtain the open loop optimal solutions. As preliminary results showed, the structures of these solutions are in fact the copies of some simple switching patterns. Therefore, it might be possible to synthesize them later in order to get the close loop system. However, experimental validation will be crutial here.

Now we give a general procedure to obtain the open loop solutions. We consider the following optimal control problem

$$\begin{aligned} & u^* = \arg\min_u J(x,u) = \frac{1}{2}\int_0^T \left(\bar{x}^T Q \bar{x} + u^T R u\right) dt, \\ & \text{s.t.} \quad \dot{x} = Ax + \sum_{i=1}^{m} u_i B_i x + F(x), \quad x(0) = x_0, \quad u \in \mathcal{U} = [u_{min}, u_{max}]^m . \end{aligned} \tag{2}$$

By $\bar{x}$ we denote here the vector of displacements, velocities or accelerations, depending on the objective of control. Under the assumption, that the problem (2) is convex and the optimal solution u^* is in the interior of $\mathcal{U}$ we can apply the first order necessary condition. For that purpose we introduce the Hamiltonian $\mathcal{H}$ and the adjoint state p as follows

$$\mathcal{H} = p^T\left(Ax + \sum_{i=1}^{m} u_i B_i x + F(x)\right) - \frac{1}{2}\left(\bar{x}^T Q \bar{x} + u^T R u\right), \quad \dot{p} = -\frac{\partial \mathcal{H}}{\partial x}, \quad p(T) = 0 \tag{3}$$

The necessary optimality condition states that

$$\Delta_{u^*} J = -\frac{\partial \mathcal{H}}{\partial u^*} = 0 \tag{4}$$

Numerical computations, based on the method of steepest descent, can be performed by proceeding the following steps

S1 Guess initial control u_0, set $k \leftarrow 0$.

S2 Solve the state x equation (1) by substituting $u \leftarrow u_k$.

S3 Solve the adjoint state p equation (3) by backward integration.

S4 Compute the descent direction $d_k = \frac{\partial \mathcal{H}}{\partial u}$. If $||d_k|| < \varepsilon$, then $u^* \leftarrow u_k$ and terminate the procedure.

S5 Choose step size λ_k such that $u_{k+1} = u_k + \lambda_k d_k$ respects the constraints i.e. $u_{k+1} \in [u_{min}, u_{max}]^m$. Optionally perform the line search.

S6 Set $u_{k+1} \leftarrow u_k + \lambda_k d_k$, $k \leftarrow k + 1$ and go to S2.

3. Experimental research

The numerical model was first elaborated. It should enable verification of both real objects and our model stand. A simplification of a moving vehicle to a single point load is excessive. In practice we require much more complex mathematical model to approach a physical object. Vibration of wheelsets and the coupling of vibrations through wheelsets must be taken into account. Analytical solution of the extended model is practically impossible. Approach methods applied to the correct numerical model enable us to obtain sufficiently accurate results. In the project we developed and applied the numerical formulation of the inertial moving load to wave problems [7, 8, 9], at the variable speed of motion. For this purpose, we applied the space-time element method. It allows us a relatively simple and direct description of the moving point mass in time. Numerical simulation in the case of wave approach, i.e. in the case of around critical speed, requires great mathematical care. Otherwise we obtain wrong solutions. Commonly used commercial software packages do not support simulations of the inertial moving load problems.

Models of a track are based on a system of continuous beams (Euler or Timoshenko model). Semi-active dampers are placed between two parallel beams – a supporting and a contact one. They are spread over the length of a track or placed just in selected points. Forces generated by dampers are proportional to the relative speed of its two ends. Damper can generate at least two different values of damping, so parameters in the system can be switched. In addition, the switching possibility should be performed within a short distance of the load passage, several to tens centimeters.

Verification of optimal control algorithms for MR dampers requires experimental investigation of the real object. For this purpose, the concept and design of the experimental test stand has been developed. The model of a boogie was accelerated to a fixed speed, then travelled with a constant speed and after a certain distance decelerated to zero on the final support. Due to the deflection of the rail guideways are selected without the supporting beams. The stiffness of the rail results in the vertical displacements in the range ±17 mm for the mass load 6 kg moving at the constant speed 4 m/s. The limit displacements of the dampers are ±25 mm and the same are limit displacements of the guideway. The efficiency of the experiment is ensured when the amplitude of damped points increases 5 mm. In such a case we can fix our dampers directly to the beams, without supplementary leverage increasing their range of work. The LORD's magnetorheological dampers were used in the stand. Manufacturer of the dampers provides only minimal information about his product. All the other required dynamical data must be determined experimentally at start, i.a. the longitudinal stiffness of the damper caused by gas cushion located in its interior. The gas spring stiffness of the damper was $K_s = 2.66 \div 9.47$ kN. The largest value of the rigidity corresponds to the displacement of 12 mm and the smallest one corresponds to the maximum range of motion of the piston 50 mm.

In addition, the analysis of boogie carrying a moving inertial load was done. The relatively large deflection of the rail could jam the trolley. The drive will be performed with a stepping motor. It is powered by pulse electric current, which means that its rotor is not rotating in a continuous movement, but does the rotation angle of a strictly fixed at every time step. The advantage is the possibility of very rapid acceleration and braking the moving object. This engine via a toothed belt would enable to disperse and stop the weight of 6 kg through 4 m.

The foundation of the test stand is the steel frame. The proposed design of the frame is a multi-section truss. It consists of two-meter components. This allows a simple modification of the test stand, adjusting them to the longer track. In this case, we only need to replace the guide rail and a toothed belt and add a simple truss segment. In the case of foundation plate would not have such possibilities. In addition, taking a lighter frame with the independent ballast will provide greater mobility of the test stand.

The results obtained by numerical simulation enabled the selection of appropriate displacement and acceleration sensors in the track measurement in the test stand. Complete diagram of the measurement sensors has been developed. Measurement of the vertical rail displacement caused by the moving mass will be used laser displacement sensors. These transducers are the best solution. This follows from the fact that laser sensors measure the non-contact method, so it does not introduce disorders into the investigated system. In addition to the laser displacement sensors will be used acceleration sensors with very low weight. Computer model of the test stand with the measurement instrumentation is performed on Fig. (1).

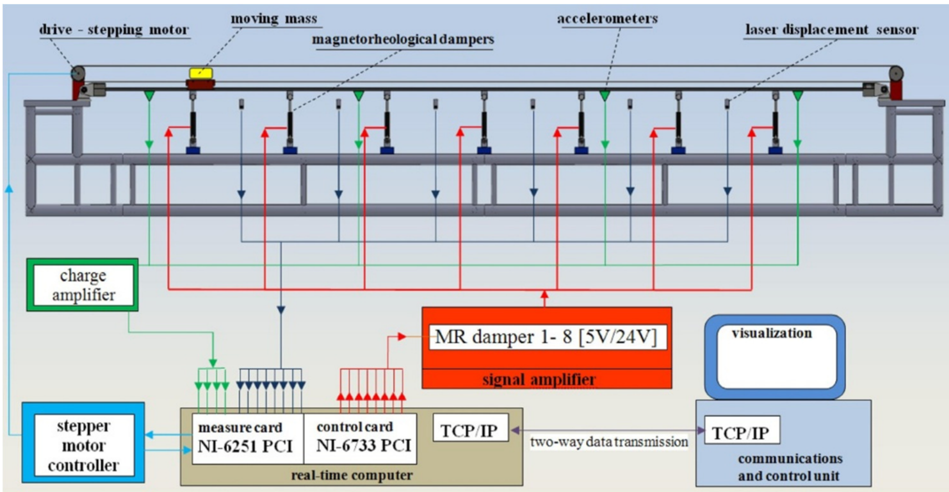

Figure 1. Scheme of the test stand

4. Conclusions

As a result of the project we will elaborate a proposal for a new design of a track. Well designed semi-active control system can be an attractive solution for building protection against surrounding infrastructure. In particular for many priceless monuments, located in town centers and exposed to destructive action of the public railway transport, only the additional smart damping system can be a successful solution to maintain their viability. The low susceptibility of the material, that the monuments are built of, does not succumb to excessive momentary or long-term deformation. The solution for this problem is a concept of modification of the track structure. Semi-active damping layer incorporated into the track can reduce vibration levels propagating into the ground in more efficient way than the traditional vibroisolation.

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