Mechatronically Controlled Bogie of High Speed Train

Filip Jeniš(✉) and Ivan Mazůrek

Brno University of Technology, Brno 616 00, Czech Republic
Filip.Jenis@vutbr.cz

Abstract. With the development of high-speed rail, the requirements for control the motion of rail vehicle bogies are increasing. The chassis setting is responsible for the safety and comfort of the vehicle. The main problem is the conflict of the damping requirements for different driving modes. On one hand, it is necessary to ensure the stability of the bogie on a fast straight track and, on the other hand, it is good curving performance. The contribution will discuss the possibilities of mechatronic control of high-speed rail vehicle bogies to solve this conflict. There are two ways: control of the individual wheelsets and control of the entire bogie. The control can be implemented by actuators or dampers in adaptive or semi-active mode.

Keywords: railway vehicle · semi-active · control · magnetorheological · damper · hunting

1 Introduction

Currently, high-speed rail transportation is developing in Europe. There is no worldwide norm for high-speed rail parameters, but in general, high-speed train's speed reach at least 200 km·h^{-1}.

As the speed of the trains increases, various problems that need to be solved, appears. Safety, comfort, and economy, can be considered as major areas of increased requirements. Safety mainly relates to vehicle stability and braking. With higher speed, the probability of hunting oscillation increases, which increases the risk of derailment. At the same time, crew comfort is reduced, and wear on both the chassis components and rail superstructure increases, thereby increasing maintenance costs. The transfer of vibrations from the rails to the body and the tilting of the body in curves fundamentally affect comfort. An equally important aspect is the economy. We can divide it into the costs of track and train chassis maintenance and traction costs – related to aerodynamics and smooth running.

The biggest problem seems to be a contradiction in the requirements for the bogie damping system when driving on a straight track at high speed and when entering the arch of small radius. In the first case, the stability achieved by the high damping is critical, in the latter case, the damping forces must be minimized to make the bogie easy to move, thereby reducing the lateral force of the wheel on the rail. Thus, there is a problem

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with conflicting requirements, which can hardly be solved with conventional passive dampers.

The solution may be to use a semi-active or active damping system. The active system contains actuators instead of springs and dampers, so it can move the bogie according to the actual needs. However, this system is very complicated, expensive, energy-intensive, and demanding to perform a fail-safe system. The alternative is semi-active damping, whereby the damping force can be changed based on the control signal. The passive damper can be exchanged for an active element with relatively small changes in vehicle construction.

2 Material and Methods

First, the railway chassis will be briefly described, followed by the areas of semi-active and active chassis control.

2.1 Railway Chassis Construction

The chassis of a railway vehicle can be divided into three various masses:

- wheelset (unsprung mass)
- bogie frame (primarily sprung mass)
- body (secondary sprung mass).

There are two types of springs and dampers between these masses:

- primary – between the wheelset and bogie frame protects the chassis against damage from vibrations from wheel/rail contact
- secondary – between the bogie frame and the body – their benefit is mainly the vibration isolation of the body and the associated crew comfort

The bogie moves in all six degrees of freedom, but it is sprung and dampened only in some. Mounting in some directions is rigid, for example using silent-blocks.

The springing is realized primarily in the vertical direction. As the primary suspension, the screw springs are usually used. Leaf springs can be also seen especially on older vehicles. Vertical secondary springing is realized with adjustable airbags, or with flexi-coil springs, which are screw springs that also provide rigidity in the lateral and longitudinal directions [2].

Primary dampers are usually used only for the vertical direction. Secondary dampers can be divided into vertical, lateral, and yaw dampers (Fig. 1).

Today, hydraulic dampers are most commonly used. Frictional dampers have been used formerly. Recently, damping systems that are controlled, either semi-actively or actively, have begun to come to the fore.

In general, three management strategies can be distinguished:

- selective frequency damping (only on the frequency of undesirable oscillation)
- train motion-based algorithm
- forward-tracked rail tracking algorithm

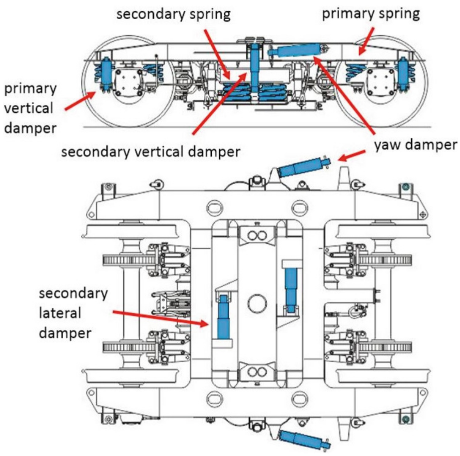

Fig. 1. Train bogie scheme [1].

2.2 State of the Art of Increasing Comfort

The importance of passenger comfort rises with increasing speed. It can be increased by semi-actively controlled secondary dampers, either vertical or lateral.

Lau studied the effect of the lateral secondary damper on driving comfort, using a hydraulic passive damper and an MR damper with a maximum damping force of 12 kN and a dynamic range of 6 [3]. The semi-active algorithm is very simple, switching between Low and High mode if the lateral velocity of the body exceeds the certain critical value. The simulations were performed on a complex two-bogie dynamic model. The lateral vibration of the body was reduced by 39% with semi-active control compared to passive damping.

Codeca on a realistic laboratory stand experimentally tested the effect of a semi-actively controlled lateral secondary damper on the bogie vibration [4]. ISOCOMP electro-hydraulic dampers developed specifically for this application with a dynamic range of 8 and a response time of 30–100 ms were used. When mass moving at 0.5 Hz, 100 ms is a 1/20 of period and that is sufficient for semi-active control. Four semi-active strategies were used: Skyhook, Acceleration Drive Damping, SH-ADD, and Mix-1-control. The lateral accelerations of the body and the bogie are used as input variables of the algorithm. The stand was excited by a signal reproducing real measurements on the track at high speed. The best results were achieved using the SH-ADD strategy reducing the vibration by 34% compared to the passive damper.

Hudha introduced two types of skyhook algorithm: body-based and bogie-based skyhook. The first represents the imaginary connection of the body to the sky, the second represents the imaginary connection of the bogie to the sky [5].

$$C_{body} = \begin{cases} C_{body,max} \; if \; V_{body} \cdot V_{rel} \geq 0 \\ C_{body,min} \; if \; V_{body} \cdot V_{rel} < 0 \end{cases} \tag{1}$$

$$C_{bogie} = \begin{cases} C_{bogie,max} \; if \; V_{bogie} \cdot V_{rel} \geq 0 \\ C_{bogie,min} \; if \; V_{bogie} \cdot V_{rel} < 0 \end{cases} \tag{2}$$

C_{body} [Nsm^{-1}] damping coefficient for body-based skyhook.
C_{bogie} [Nsm^{-1}] damping coefficient for bogie-based S-H.
V_{body} [ms^{-1}]lateral velocity of the vehicle.
V_{bogie} [ms^{-1}]lateral velocity of the bogie.

The lateral secondary MR damper, which is implemented in the model according to the Bouc-Wen model [6], was controlled by a semi-active algorithm. Simulations were performed on a 17 DOF rail vehicle model. The system was excited with a sine wave of 0.07 m amplitude and frequencies 1, 3, and 5 rad·s^{-1}. Three criteria were evaluated: lateral deflection, rolling, and yawing in the center of gravity of the body. Bogie-based skyhook achieved better results, it improved all criteria.

2.3 Current State of Art in Wheelset Motion Control

The hunting oscillation of the wheelset is self-excited motion and it is caused by the forward speed and tangent forces in the wheel/rail contact. These forces are caused by the contact profile conicity and the contact geometry slip characteristic. This oscillation leads to a reduction in the comfort and wear of the wheel/rail contact.

The hunting oscillation limits the maximum speed of the train because to maintain safety, the critical speed of a vehicle must be higher than its maximum operating speed. Removing the stability problem and thereby increasing the maximum speed can be achieved by controlling the wheelset motion. Either longitudinal primary semi-active dampers or active actuators can be used to control the wheelset. At the same time, this control improves curving performance – the lateral forces of the wheel on the rail decrease, thereby reducing wear and maintenance costs of the tracks.

Shen explored the possibility of increasing train stability and reducing wear by longitudinal actuators between the wheelset and the bogie frame [7]. In his paper, two control strategies are described:

1) Open-loop, where the required angle is generated and the actuators rotate the wheelset to this angle,
2) Closed-loop – the wheelset is rotated so that its yaw torque is reduced to zero, whereby an ideal curving performance should be achieved.

The second method is further studied. The yaw moment is measured by the wheelset lateral displacement relative to the bogie frame, with the known stiffness of the mounting. With this strategy, it was possible to reduce the lateral force to the track by at least 50% compared to passive damping.

Peréz introduced 3 active wheelset control strategies reducing vibrations on straight track, lateral wheel forces on the rail, and wear when passing through an arch [8]. Strategies differ in input variables. In the case of the first strategy, the lateral displacement of the wheelset is sensed. The second strategy uses torque around the vertical axis and the input for the third strategy is an angle between the wheelsets. The passage of the 1357 m radius arc at 230 km·h^{-1} was simulated. The results of all three strategies are similar, which means that wheelset lateral displacement is reduced by about 70%, the force on the rail by about 45%, and wear by about 80% compared to the passive solution.

Mei compared the following three strategies:

1) active control of a conventional wheelset,

2) active control of a wheelset with independently rotating wheels - IRW,
3) active control of the wheelset with independently rotating wheels, each wheel having its own axis – DSW [9].

All three strategies significantly reduce lateral displacement. With DSW the displacement drops to almost zero.

Fotouhi used both longitudinal and lateral primary actuators as a damper [10]. They are controlled by a simple adaptive algorithm that increases the damping level if the vibration exceeds a set limit. The excitation is a sine sweep from 0 to 50 Hz with an amplitude of 5000 N. The vibration in both directions was significantly reduced. Thanks to this strategy, the stiffness of the suspension can be low, which improves driving performance and reduces wear.

Wei studied the possibility of reducing wheelset vibrations using semi-actively controlled longitudinal primary dampers [11]. He used a 17 DOF dynamic rail vehicle model with two bogies created by SIMPACK. Two strategies were used to control dampers:

1) skyhook algorithm – the input variables are the wheelset and bogie angle and the relative angular velocity between wheelset and bogie,
2) the damping force calculation using the Dahl model of MR damper [12]. Passage through an arch of the 600 m radius. Strategy 1 is more effective. Wheelset lateral displacement is reduced by at least 20%.

Bombardier is experimenting with the active turning of wheelsets. MITRAC 500 drives are used for lightweight rail vehicles [13]. One side of the wheelset is fixed, the other is controlled by an electro-hydraulic actuator – the wheelset is rotated around a vertical axis. Thanks to the technology of active radial control and stability control, it is possible to close the gap between stability and curving performance. This solution promises to reduce wheel and rail wear, vibration, and noise.

2.4 Current State of Art in Bogie Frame Motion Control

The second way to increase the critical speed by limiting hunting oscillation of the wheelset is to increase the torsional rigidity between the bogie and the body. For this, the dampers are replaced by the active elements. In addition, the bogie can be turned into curves, thereby reducing the wear of the track superstructure and maintenance costs.

Braghin say that the problem of yawing cannot be solved by hydraulic dampers because of their internal flexibility [14]. Therefore, the passive damper was exchanged for the actuator designed in such a way that it could be simply mounted instead of a conventional damper. The proposed control strategy aims to achieve both increased stability on the straight track and improved curving performance. The applied force is calculated from two components:

$$F_{ref} = F_{ref_S} \cdot F_{ref_C} \tag{3}$$

F_{ref} total reference force.
F_{ref_S} force providing stability, damping effect.
F_{ref_C} force to improve curving performance.

To ensure stability, the actuator acts as a damper:

$$F_{ref_S} = -(c_v \cdot v_{rel} + m_v \cdot a_x) \tag{4}$$

F_{ref_S} force providing stability, damping effect.
c_v damping coefficient.
v_{rel} relative velocity between bogie and body.
a_x longitudinal bogie acceleration.

The second equation member (F_{ref_C}) compensates inertial forces acting on the actuator and some effects of the velocity sensor delay. The strategy to improve curving performance is based on the idea of balancing the forces acting on the first and second wheelsets. The yaw moment is a function of the lateral acceleration of the bogie and the arch radius. The measured variables used to determine the reference force are the forward speed of the train, the inclination of the train in the arch, and the lateral acceleration of the bogie. The radius of the arch is estimated from these variables. If the estimated radius is above the specified value, the corresponding reference force component will be zero (F_{ref_C}). In other cases, the yaw torque and associated forces to align it are determined. The torque is determined by measured data and a table of values determined on the base of a mathematical model and experimental tests. Numerical simulations on a complex multibody model have shown that the strategy works. The difference between the forces on the first and second wheelsets when passing through the arch decreased about 20%.

Matsumoto is also trying to solve problems with the actuators. The force of the actuator is calculated as follows [15]:

$$F = k(R_c) \cdot \rho \tag{5}$$

F [N] actuator force.
k [-] scaling factor.
ρ [ms^{-1}] estimated rail curvature.
R_c [ms^{-1}] constant curve radius.

The scale factor k is dependent on the constant radius of the arch R_c and it is setting iteratively so that the lateral contact force on the front wheel is zero. Lateral contact force was reduced mainly for small radii, about 50% for a radius of 200 m, as shown in the simulations on half-train model experiment.

Sun simulated the effect of semi-active secondary lateral damper control on chassis vibration and critical velocity [16]. To simulate, he used the combination of a multibody model of a railway vehicle in Adams/Rail and a control strategy in Matlab/Simulink. The MR damper was modeled as the Bouc-Wen model [6]. The control strategy was performed as a combination of Skyhook and Groundhook.

$$F = F_{sky} + F_{gnd} \tag{6}$$

F [N] complete force.
F_{sky} [N] force generated by skyhook algorithm.
F_{gnd} [N] force generated by groundhook algorithm.

The control variables are the lateral velocity of the bogie and of the body. The critical speed is 275 km·h-1 with the damper in the deactivated state, 319 km·h-1 in the activated state and it was increased to 328 km·h-1 when using semi-active mode. Thus, the stability of the train appears to be dependent on the set of the lateral secondary damper.

Goodall [2015] also dealt with replacing a passive damper with an actively controlled actuator. The simulations were performed on a half railway vehicle model. The model is equipped with virtual sensors measuring the following variables: lateral acceleration of the body, relative lateral displacement between bogie and body, the bogie lateral acceleration, yaw angular velocity of the bogie, lateral acceleration and yaw angular velocity of the wheelset.

Two control strategies are proposed:

1) control with full state feedback (LQR),
2) control with state estimation (LQG) – replaces sensor data with an estimate from Kalman filters to avoid possible problems caused by stochastic errors.

With this active control, it is possible to reduce the stiffness of the primary suspension to 10% while reducing the vibration rate to 71%.

Liebherr has started to produce electro-hydraulic actuators for lift-off flaps. Step by step, he came to the production of EHA actuators for control train bogie [17].

3 Results and Discussing

3.1 Control of the Body Movement

Most studies deal with the control of body movement to increase crew comfort. It turns out that it is possible to reduce the body vibration by 30–40% when changing passive lateral secondary dampers to semi-actively controlled MR dampers [3, 4]. The control strategies are most often based on the skyhook algorithm [18]. However, satisfactory results can also be achieved with a simpler adaptive ON/OFF algorithm that will increase the damping level when the specified vibration value is reached [3]. Skyhook can be based on damping the motion of the bogie or of the body [5]. Combining Skyhook with other strategies, such as ADD control, can also help reduce vibration [4]. In this paper, only a fraction of the studies that are interesting by used semi-active algorithms is presented.

3.2 Approaches Solving the Gap Between Stability and Manageability

Another frequently solved problem is the mentioned contradiction in the damping requirements for straight track and for the passage of arch with a small radius. There are two different approaches to solve this problem.

Control of Wheelset Motion

The paths to this control are 3: use of primary longitudinal dampers between the wheelset and the frame, which are controlled either adaptively or semi-actively, or the use of active actuators in the same place.

Good results of the wheelset vibration reduction are achieved by the semi-active Skyhook algorithm, similar to the elimination of unwanted motion of the body [11]. But satisfactory results can also be achieved with an adaptive algorithm [10]. The control is, in most cases, performed by actuators. The most usual input variable is the lateral displacement of the wheelset, but it can also be the wheelset angle to the bogie [8], or the combination of the wheel-to-bogie angle and the difference in wheelset and bogie angular velocity [11]. The best results of active control are achieved when individual wheels are independently mounted [9]. However, independent wheel positioning means dramatic changes to the bogie frame – this principle is therefore unusable for current vehicles.

Further, railway vehicles do not use primary dampers in the longitudinal and transverse directions, therefore the application of the wheelset control technology would mean structural modifications to the bogie frames. Hence, it will be used in a new generation of vehicles.

Control of Bogie Frame Motion

The second approach to solve the damping requirements contradiction is to control the lateral or yaw motion of the bogie. Control of yaw motion is always secured by active actuators located in place of yaw dampers. The lateral position of the bogie can be controlled by secondary lateral dampers.

The idea of control is to reduce lateral forces to the track, thereby reducing wear and maintenance costs. To make the train turn, a certain guiding force is needed and therefore the lateral forces can not be reduced to zero. The aim is therefore to balance the force from the first and second wheelsets in the arc, thereby reducing the maximum force [14, 15]. On the straight track, a strong damping level is then set to eliminate the hunting of the wheelset.

With bogie motion active control, the primary stiffness can be reduced to 10% while reducing the vibration rate to 71%, compared to the use of passive dampers [19].

By controlling the lateral position of the bogie with the secondary lateral MR damper using Skyhook and Grounghook algorithm, the critical train speed can be increased, but only 3% compared to the bogie damped by the MR damper in ON mode. However, the stability of the vehicle is very dependent on the damping level of the secondary lateral damper [16].

This technology is directly applicable to current trains that have the ambition to increase their maximum speed, because almost each rail vehicle has the yaw dampers. For the time being, no one has studied the bogie control with the MR yaw damper.

3.3 Undescribed Part of the Knowledge

The main unexplored area is the possibility of solving the above-described contradiction in the damping requirements by semi-actively controlled bogie motion, using yaw MR dampers.

Elimination of Yaw Oscillation of Bogie by Yaw MR Damper

The dampers should increase the stability and a maximum speed of the train by semi-active control. When passing through an arch, the damping level would be minimal to avoid unnecessary stress on the tracks and their wear.

Turning the Bogie into the Arch with Yaw MR Damper

Algorithms try to keep the sprung mass in the desired position. In theory, therefore, it should be possible to rotate the bogie as needed. The method will have its logical limits – displacement of the mass from the starting position will mainly limit the stiffness of the springs and also greatly depend on the frequency and amplitude of the exciting motion. Nobody has published anything like that yet.

The efficiency of the Algorithm According to the Input Variables

The previous two points relate to the fact that the efficiency of the algorithm will also depend on what variables are used as input. There are two main possibilities, control by lateral velocity and acceleration or by angular velocity and acceleration.

The efficiency of the Algorithm According to the F-v characteristics of the Damper

The function of the algorithm will also be dependent on the F v characteristic of the damper, the slope of the F-v curve before and after the knee, and the knee position.

Influence of the Damper Response Time

Studies often neglect damper response time in simulations. The long response time significantly degrades the results of the used control strategy. The faster is the motion we want to attenuate, the higher is the influence of the response time.

The yaw oscillation frequency of the bogie is about 5–6 Hz [20], which is a relatively low frequency. Theoretically, the damper response time up to 16 ms should not be such a problem. The real MR response time ranges from 1.5 ms for the ultra-fast damper [21] to 300 ms [4], which will certainly cause a difference in the efficiency of the semi-active control.

Influence of the damper dynamic range

Similar effect as time response has dynamic range – the ratio of damper coefficient in activated and non-activated state. Logically, the larger the dynamic range, the more efficient the control. In simulations, it is popular to set the damping force to zero in the inactivated state, but this never happens. The real dynamic range is from 2 to 10 [22].

4 Conclusions

The study of semi-active and active control of rail chassis dampers covers two areas, increasing comfort and solving the contradiction between damping requirements for straight track and for passing the arch with a small radius. Secondary lateral MR dampers are used to increase comfort. The contradiction in the requirements is solved by controlling the wheelset using a longitudinal primary MR damper or actuator and by controlling the motion of the bogie using actuators. Nobody has dealt with the control of bogie motion with the yaw MR damper, so there is an area for further research.

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