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Experimental Assessment of Active Wheelset Steering System Using Scaled Roller Rig

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Abstract. The paper is created within the project which aim is to design a system of active wheelset steering for an electric four-axle locomotive. The wheelset steering system enables reduction of forces acting in the wheel-rail contacts in a curved track and consequently a reduction of wear and maintenance costs of both vehicles and rails is achieved. The project consists of three main parts: computer simulations, scaled roller rig experiments and field tests. The paper is focused on the second part on the project. The scaled roller rig has been innovated in order to simulate bogie run in a curved track with uncompensated value of lateral acceleration and instrumented with a system of measurement of lateral wheel-rail forces. The experimental bogie has been equipped with systems of active wheelset steering and measurement of axle-box forces. The experiment setup, newly developed and applied systems of forces measurement and wireless signal transmission, and results of the first experiments are described in detail.

Introduction

Force interaction in between rails and railway wheels is one of the most important issues in the development of the new rolling stock. Todays' effort to build an economic and environment friendly railroad brings a general and sustained demand to reduce wheel-rail contact forces below legislative limits as much as possible. Particular attention is paid to the lateral component of wheel-rail contact forces during passing a curved track, also called guiding forces. Conventional methods of reduction of guiding forces are based on the optimization of suspension characteristics [1], or on mechanic or hydraulic linkages between the various components of the running gear. Because the possibilities of conventional methods are increasingly encountered at their limits, ideas of the utilization of active controlled elements in the wheelset guidance and railway vehicle suspension occur [2, 3]. One of the first practical utilization of such systems are active yaw dampers developed by Liebher and offered as an option for Siemens Vectron locomotives [4] (Fig. 1).

In order to compare the effectiveness of individual methods for reducing guiding forces, a simplified multibody simulation (MBS) model of an electric locomotive has been created (Fig. 2). The model consists of 7 rigid bodies (car body, 2 bogie frames, 4 wheelsets) that are connected by linear force elements. Wheel-rail contact respects non-linear characteristics of S1002 wheel and UIC 60 rail profiles, forces acting in the wheel-rail contacts are calculated using FASTSIM method [5].

Fig. 1: Active yaw damper on Siemens Vectron MS locomotive for ÖBB, Innotrans fair 2018 (photo author)

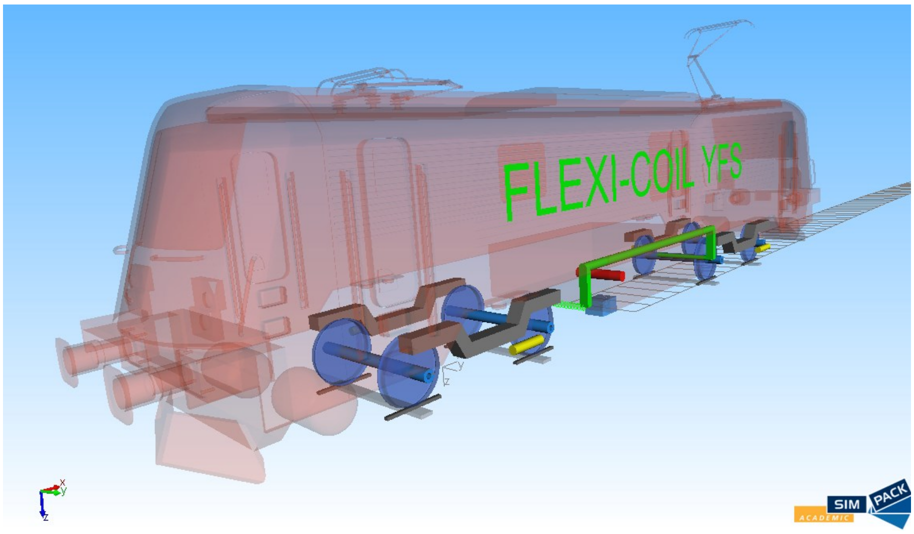


Fig. 2: Graphical representation of the simulation model

Using this model, a simulations of vehicle run in a low speed in the curved track of radius R = 150 m considering the friction coefficient in the wheel rail contact f = 0.4. The quasistatic value of guiding forces in a constant curvature track without irregularities Y_{qst} was evaluated on all wheels. A vehicle setup and parameters has been sought in which the value of Y_{qst} is minimized. The maximum value of Y_{qst} is typically reached on the outer wheel of the first wheelset. Simulations were performed for 6 different vehicle setups:

- STD – Standard, the suspension parameters corresponds to the standard 4-axle electric locomotive with flexi-coil type secondary suspension.
- YFS – Yaw Flexible Suspension, the characteristics of the primary suspension and wheelset guidance are modified in order to soften the yaw stiffness of the connection between wheelsets and bogie frame.
- MBC1 – Mechanical Bogies Connection Type 1, one of the classical methods of reducing guiding forces based on the direct mechanical connection of bogie frames [6].
- MBC2 – Mechanical Bogies Connection Type 2, mechanical connection of bogie frames by a mechanism. This method woks on the similar principle like MBC1, but has

less space demands. Thus MBC2 can be utilized also on asynchronous locomotives, which have usually a large transformer located between the bogies.

- AYD – Active Yaw Dampers. Method based on active controlled yaw torque acting between car body and bogies. The torque is generated by a couple of linear actuators acting in between each bogie frame and car body [7].
- AWS – Active Wheelset Steering, yaw angle of wheelsets towards a bogie frame is actively controlled.

The parameters of mechanical bogie connections MBC1 and MBC2 (ie. stiffness and preload od coupling elements) were optimized in order to achieve the best performance in a 150 m radius as well as the force produced by AYD actuators and the wheelsets yaw angle for AWS. The Fig. 3 and Table 1 thus expresses the maximum possible effect of reducing the guiding forces, which can be achieved by individual methods. It is important to note that:

- Contribution of mechanical bogie connections MBC1 and MBC2 to the guiding force reduction will be lower then calculated values 23 respectively 10.5 pro cent. The parameters of mechanical bogie connections should be compromised in the wide range of curve radiuses.
- For AYD the impact of forces in the actuators on the secondary suspension deflections was not taken into an account. To avoid undesired large deflections of secondary suspension in the lateral, direction and transmitting forces via lateral bump-stops the power of the actuators would probably have to be lower than considered in the simulation. Consequently, a reduction in guiding forces will be lower then calculated 25.7%.
- The highest reduction of guiding forces (75%) shows YFS. However, such reduction is achieved for zero value of the yaw stiffness of the wheelset guidance which drastically affect the stability and lower the maximum speed of the vehicle.

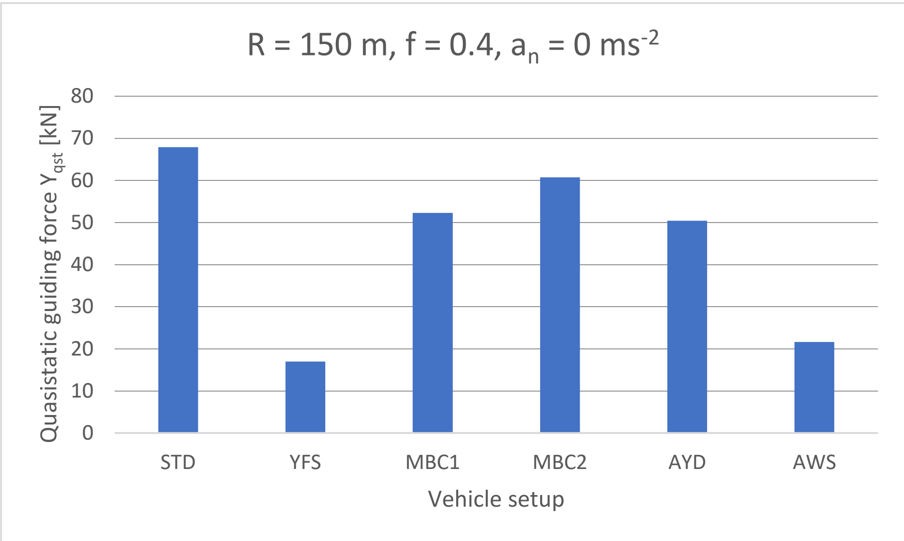


Fig. 3: Quasistatic guiding force Y_{qst} acting on outer wheel of the 1st wheelset in curve with radius R = 150 m for various vehicle configurations

The AWS appears to be the most effective and practically implementable method for the reduction guiding forces, because exhibits significant reduction of guiding forces (68.1%) and do not deteriorate other important properties of a vehicle such as forces in the secondary suspension, maximum speed, stability, ride comfort, etc. Moreover, in the performed simulation all four wheelsets were steered to the same yaw angle towards the bogie frame. The performance of AWS could be improved by individual wheelset steering and thus even distribution of guiding forces on all wheels and further reduction of guiding forces could be achieved.

Table 1: Quasistatic guiding force Y_{qst} for different vehicle setups

Vehicle setup	STD	YFS	MBC1	MBC2	AYD	AWS
Y_{qst} [kN]	67.9	17.0	52.3	60.8	50.4	21.6
Y_{qst} reduction [%]	0.0%	75.0%	23.0%	10.5%	25.7%	68.1%

In view of the above, a project with the aim of design a system of active wheelset steering for an electric four-axle locomotive was launched. The project is divided into the three main stages:

I. computer simulations,
II. scaled roller rig experiments (Fig. 4),
III. on track tests.

The goal of Stage I is composing and verification of the detailed simulation model including wheelset steering actuators and control loop and optimize the wheelset steering control algorithm considering various vehicle speeds and track conditions.

The Stage II is focused on the verification of computer simulations and demonstration of the benefits of AWS using a scaled laboratory test device.

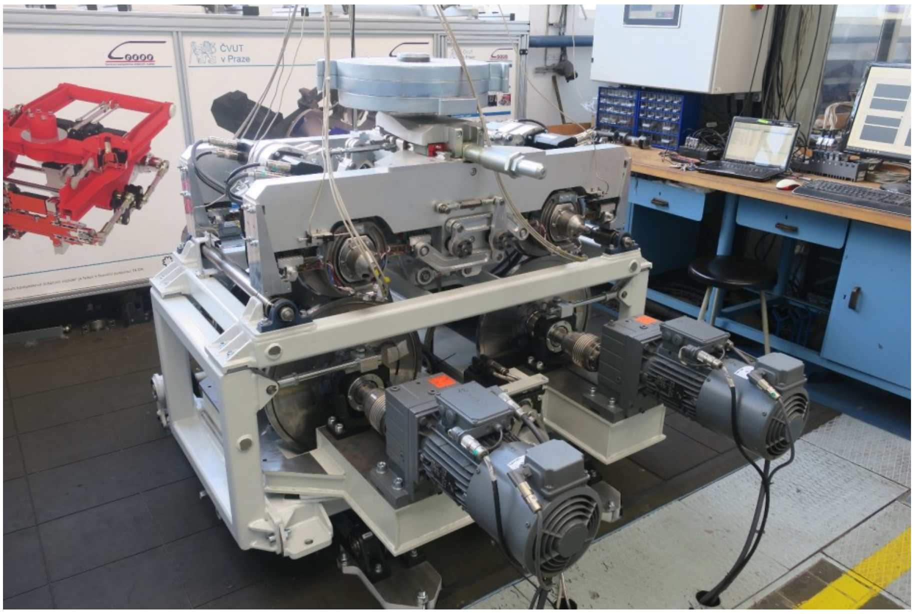


Fig. 4: Scaled roller rig of the Czech Technical University

The Stage III includes implementation of AWS system on an existing locomotive and performing the track tests. Prior to the first field tests of active wheelset steering system it needs to be thoroughly tested to meet the requirements of safety. Roller rigs can be advantageously used for these tests, because they allow testing of vehicle running behaviour in laboratory conditions, where it is possible to simulate extreme situations without a risk of railway accident [8, 9]. The principle of roller rig is in the replacement of a track by rotating rollers with a rail profile on their circumference. The tested vehicle is longitudinally fixed. Nevertheless, the creep conditions and forces in the wheel-roller contact points are analogical to the conditions in wheel-rail contacts of a vehicle running in a real track. In order to fulfil the goals of the Stage II and perform laboratory tests for the assessment of the impact of AWS on guiding forces the CTU test rig and experimental bogie had to be considerably modified. The paper focuses on the test stand design changes and the first tests that were performed to verify its function.

Roller rig setup

The CTU scaled roller and experimental bogie have been considerably improved in order to simulate bogie negotiation of arbitrary shaped track and to measure force interaction between vehicle and track. The rig capability of a curved track simulation has been extended by simulation of the uncompensated lateral acceleration. It is based on tilting of the entire rig [10]. The completely new main frame of the rig, that is supported on four rollers, has been designed, manufactured and assembled. (Fig. 5). Thus the CTU roller rig is capable to simulate vehicle run in straight, transition and constant curvature track up to radius of 15 m and rail cant deficiency up to 200 mm.

Special attention was paid to measurements of forces in the wheel-roller contacts and between wheelsets and bogie-frame. Lateral components of the forces acting in the wheel-roller contacts are measured by strain gauge measurement of roller disc deformation [12]. The own telemetry system of wireless signal transmission from the rotating roller has been developed (Fig. 4, left) [10].

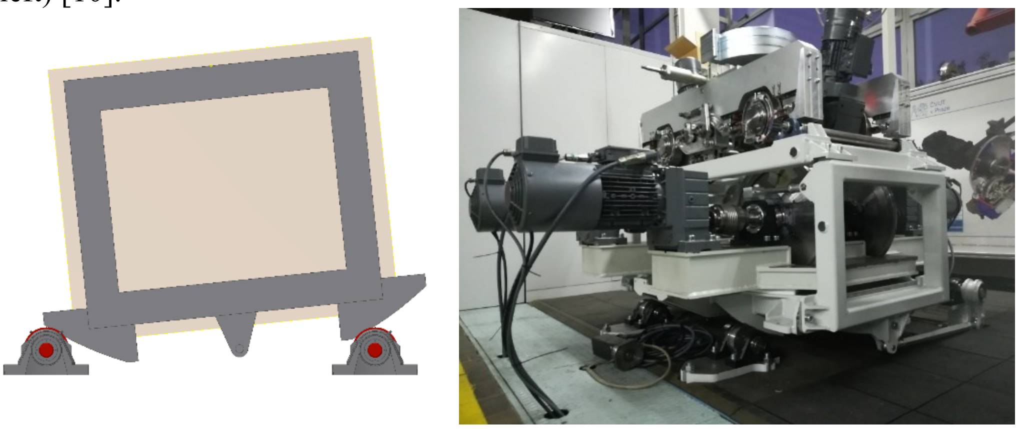


Fig. 5: Principle and design solution of the roller rig tilting

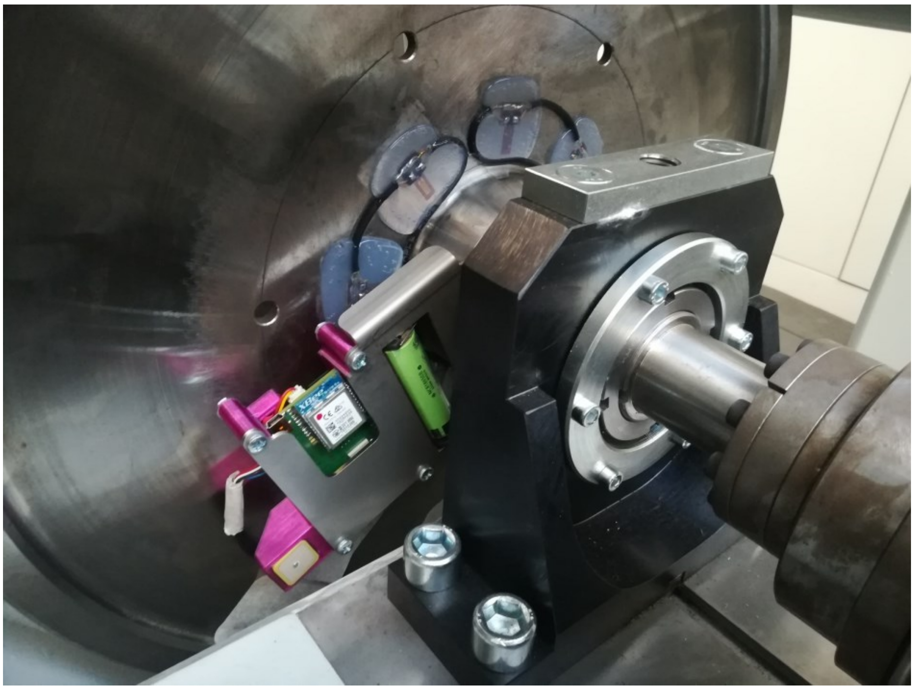


Fig. 6: Strain gauge instrumented roller with wireless transmitter module

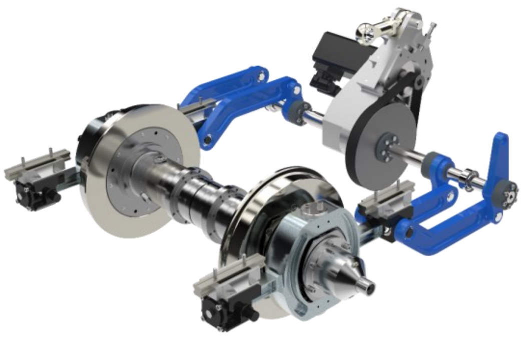
The instrumented rollers have been calibrated by loading by directly measured lateral force. The loading was gradually performed at 16 points on the roller. The maximum error is 2.5% in the range of 0.1 – 1 kN. Although the roller rotates in the speed up to 1000 RPM, the calibration constants are not influenced by rollers speed. The measured signal is wirelessly transmitted in 1 kHz sampling rate to the standard PC and further processed in LabView software. The signal transmission is realized independently for each roller, time synchronisation of the signals is done by global positioning system (GPS) clock signal. The wireless signal transmission has been broadly tested, the number of lost samples is less than 0.05%. The measured signal is in parallel saved without lost samples to the SD card which is attached to the transmitter on the roller.

Experimental bogie setup

The experimental bogie is 1:3.5 scaled, but it does not correspond to any specific bogie of a real vehicle [13]. Its design is based on the goals of experimental research. In order to achieve high geometrical accuracy, the most of the main structural parts are made of aluminium by CNC machining. The connections of the mutually movable components are provided by roller and linear roller bearings, dry friction joints are avoided.

Wheelset steering mechanism.

The wheelsets are steered by an actively controlled steering mechanism (Fig. 7). The actuator is a permanent magnet synchronous servomotor (item 1) with rated torque 2.5 Nm. The actuator torque is transmitted via toothed belt (item 2) to the steering rod (item 3) and then to the wheelset by pair of linkages (item 5). Each wheelset is controlled independently to a desired value of yaw angle between wheelset and bogie frame by analog voltage signal connected to the servomotor controller.



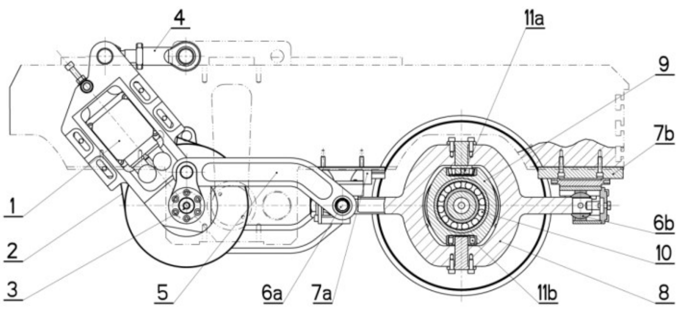


Fig. 7: Wheelset steering mechanism

Axle-box forces measurement.

The experimental bogie is equipped with a system of measurement axle-box forces, i.e. forces transmitted between axle-boxes and bogie frame.

Forces between each axle-box and bogie frame are transmitted via a stirrup (item 8 on Fig. 7), that was optimized for the strain gauge placement and serves as 3-axis load cell. Each stirrup is instrumented by 36 strain gauges connected in 3 Wheatstone bridges (Fig. 8). Thus independent measurement of longitudinal, lateral and vertical component of axle-box force is achieved [11].

The systems of wheel-roller contact force measurement and axle-box forces measurement has been successfully implemented, calibrated and tested on the rig.

Setup of experiment

The main goal of the first experiments was to verify the function of the simulation of the curved track, the test of active wheelsets steering and position control, while verifying the systems of measurement of axle-box forces and guiding forces. Two types of experiments were performed:

1. Vehicle run in superelevated straight track. During this test was the wheelset steering switched off, the bogie behaved as a standard passive suspension bogie. Straight track was simulated, whilst the rail superelavation p was continuously changed from zero to p = 28.6 mm (p = 100 mm. in a full scale).
2. Test of active wheelset steering. Test of active wheelset steering test was conducted in a curved track of a radius R = 60 m that corresponds to 210 m in a full scale. The yaw angle towards the bogie frame of both wheelsets was continuously changed from zero 0.22 deg. The yaw angle of both wheelsets was the same but in the opposite orientation.

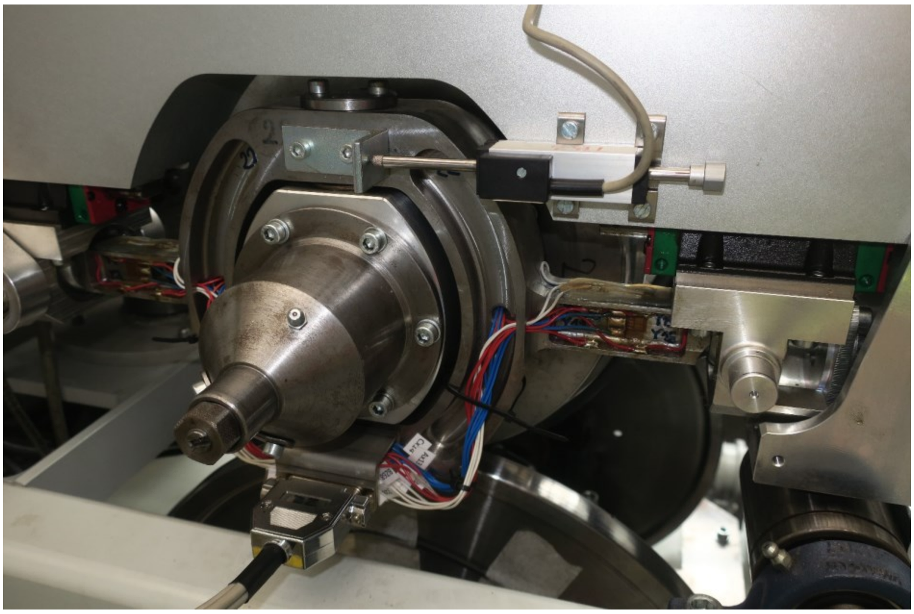


Fig. 8: Instrumented stirrup

In the experiments the yaw angle of both wheelsets, track radius and superelevation of rails were directly measured by potentiometric transducers. At the same time the guidance and axle-box forces were measured. The experiments were done in a low speed of rollers N = 50 RPM.

Results of the first experiments

Vehicle run in canted straight track. The cant angle of the track β could be expressed by:

$$\beta \cong \sin\beta = \frac{p}{2s} \tag{1}$$

where 2s is the distance of the rails in the lateral direction and p is superelevation of rails. Then the lateral a_n acceleration is given by the component of the gravitational acceleration as:

$$a_n = g\sin\beta = g\frac{p}{2s} \tag{2}$$

Lateral force F_y acting on mass m is proportional to the rail superelevation by formula:

$$F_y = ma_n = mg\frac{p}{2s} \tag{3}$$

The results plotted on Fig. 9 are fully consistent with above assumption. The red line shows the sum of the lateral component of axle-box forces across all four wheels, whilst the black line shows the sum of wheel-rail guiding forces. Both are proportional to the superelevation of rails. The difference between them corresponds to the mass of wheelsets.

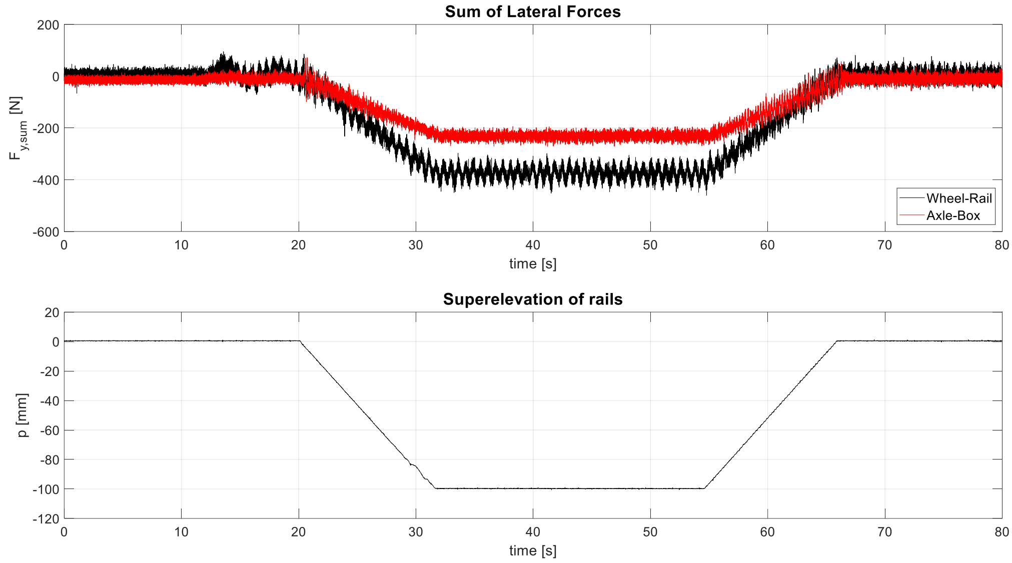


Fig. 9: Measured data – vehicle run in a canted straight track

Test of active wheelset steering. The test of active wheelset steering showed the functionality of wheelset steering mechanism and capability to steer both wheelsets to the desired yaw angle towards the bogie frame. Simultaneously the strong dependence of guiding forces on the yaw angle of wheelsets and possibility to considerably reduce guiding forces by active wheelset steering were confirmed. The plots on Fig. 10 show the time development of guiding force on the outer wheel of the 1st wheelset. This wheel exhibits the highest value of guide forces of all wheels of a bogie. With the increasing value of the wheelset yaw angle fell guiding force there below 30% of its original value.

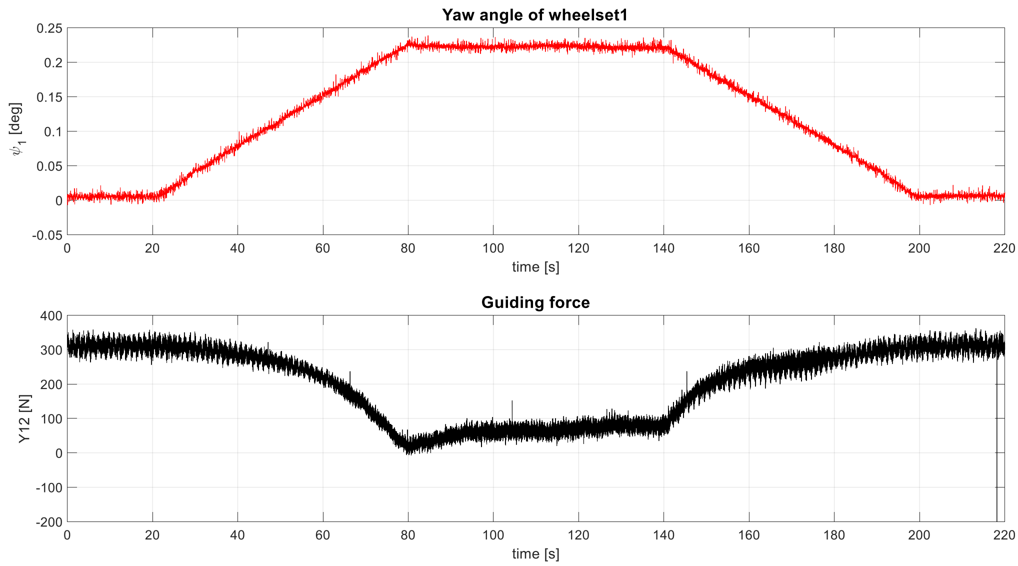


Fig. 10: Measured data – active wheelset steering test

Conclusions

The guiding forces acting in the wheel-rail contacts while a vehicle passes a curved track play very important role in the development of the new types of rolling stock. Reduction of guiding forces by conventional methods based on tuning suspension parameters and mechanical connections between bogies is not very effective. According simulations results the active wheelset steering is very effective and practically applicable method for reduction of guiding forces. Czech technical university together with industrial partner develops a system of wheelset steering for an electric locomotive. The paper focuses on the 2nd stage of the project – measurement of the performance of the system using experimental scaled roller rig. The experimental bogie has been equipped with the actuated mechanism that tis capable to steer wheelsets positions in the yaw direction and measure forces transmitted between axle-boxes and bogie frame. The roller rig was modified to fully simulate vehicle run in a curved track including effects of centrifugal acceleration and equipped with measurement of guiding forces. The performance of the experimental device was successfully tested during initial tests. The device is ready for conducting the experiments with varying speed, track radius, uncompensated lateral acceleration and control algorithms of the wheelset steering. Such experiments are scheduled as the next step in the near future.

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