Development of an actively controlled, acoustically optimised single arm pantograph

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Summary
Deutsche Bahn AG is forced to increase the efficiency of the existing overhead line system by running with higher speed than actually possible and by lowering the maintenance and operational costs on account of the reduction of wear at the same time.

As the currently used high speed pantographs have already reached their technical and operational limits, Bombardier Transportation and Deutsche Bahn AG have started a co-operative project to develop an Actively controlled Single arm Pantograph (ASP), which shows a significant reduction in contact force dynamic and noise emission and allows the operation at the heterogeneous overhead line system of DB AG with higher speed and less wear.

This paper points out the aims of the project and describes the design of a prototype already realised. First results of wind tunnel tests and examinations at a pantograph test bench will be presented. Simulated line tests, carried out with a validated simulation model of the ASP show the improvement on contact force dynamic by a two stage closed loop control circuit.

1 Introduction

In general the combination of technical progress, the knowledge about the behaviour and the limits of a system and the continuous necessity for increasing the efficiency and reducing the operational costs pushes the development and the introduction of new systems.

Since the high speed pantographs currently used, have already reached their technical and operational limits, Bombardier Transportation and DB AG have started a co-operative project in order to develop an innovative pantograph. Based on the performance level of the actual high speed pantograph DSA350SEK, which is used in different modifications on the ICE1, ICE2 and ICE3 trains, the following common aims have been defined:

- reduction of contact force dynamic by 20\% - also in multiple traction - by means of an active control circuit
  - running faster on existing contact lines without any expensive modernisation of the overhead line infrastructure
  - reduction of wear and therefore the maintenance costs as result of a lower contact force level
- decrease of noise emission for 10 dB(A) compared to the DSA350SEK - in particular at speeds above 300 km/h - by an adequate acoustically optimised design
  - fulfil lower noise emission limits, which probably will be defined in the near future
  - saving expensive noise protection barriers along the tracks
  - maintaining the effectiveness of existing barriers
- lower aerodynamic resistance of the pantograph
  - reduction of traction energy
- continuous online diagnostic of the overhead line system with help of the sensor signals of the control circuit
  - improvement of the maintenance management and the quality of the overhead line system
  - reduction of the number of great overhead disturbances
• retrofitable to consisting trains.

Whereas the reduction of noise emission by pantographs primarily is of relevance above speeds of about 300 km/h, major significance is assigned to the improvement of the dynamical interaction between pantograph and contact wire with regard to the intended and necessary increase of the efficiency by running faster on the existing overhead line infrastructure.

2 Design of the ASP

As result of extensive studies of the design of a new high performance pantograph and based on simulation results for the control design and the acoustic optimisation, Bombardier Transportation and DB AG have decided to realise a single arm, actively controlled pantograph with an one beam upper frame and a new, acoustically optimised construction of the pantograph head (see figure 1). While the mechanical design and the production of the prototype was done by Bombardier Transportation, DB AG was responsible for the control design, the simulations of the dynamical interaction with the catenary and the acoustic optimisation and the enforcement of tests and examinations in the wind tunnel, at the pantograph test bench and on the line.

**Construction**

Besides the already known conditions and inputs from the existing pantographs, the construction of the ASP additionally has to fulfil following demands:

- a generally noise optimised design, especially of the pantograph head
- controllable kinematic and dynamical qualities, this means suitable places for the implementation of the sensors and actuators with defined reactions on the contact force without stimulating any dominant resonance modes of the pantograph
- maintenance friendly and reliable in operation even with the additional active components.

For the unrestricted use at the whole overhead line system of DB AG relevant parameters like for instance the dimensions of the pantograph head, the number and distance of contact strips or the minimum and maximum working height of the pantograph have already been fixed before. The kinematic of the ASP is comparable to the SEK-type and - as result of the retrofitability required - the interfaces to the train and the fitting place on the train are identical to the actual system. As it should be possible to use the ASP - with reduced speed - in passive mode, too, the usual pneumatic rising mechanism is implemented.

With respect to the noise emission, the dimensions of the cross-sections of relevant components as the lower and upper frame, the steering bar and the apex tube have been chosen as large as possible. The parallel leading bar for the pantograph head was integrated in the upper frame arm. The base frame and the knee area will be covered, if necessary.
The pantograph head was designed completely new (see figure 2), the number of noise critical parts was reduced noticeably. In contrast to the actual high speed pantographs, acoustically optimised horns [1] are mounted directly at the contact strips.

The contact strip spring-suspension consists of two simple torsion bar springs, fixed at both ends of the apex tube and connected via lever arms and holders with the contact strips. Depending on the intensity and the place of contact force input, the lever arms rotate round the torsion bar springs axis and the contact strips move up and down. The contact strip holders are prepared at both sides for pick up the necessary force and acceleration sensors for measuring the contact force as controlled variable. Horizontal working springs, mounted between the upper lever arm joints and the contact strip holders, leading to an additional elasticity of the contact strips in driving direction and reduce the amount of damages of the contact strips, caused by horizontal shocks.

**Control design**

Aim of the control circuit is to influence the movement of the pantograph by the actuators in such a manner that the contact force fluctuation will be reduced significantly. Besides fixed operational instructions, the requirements on the control system also depend on the basic mechanical construction of the pantograph as well as on the location of the actuators and the resulting transfer characteristics of the controlled system including the overhead line system.

As it is not possible to describe the dynamical characteristic of the overhead line system in a closed mathematical function, it is necessary to define a valid, simplified overhead line model firstly and use this approximation together with a model of the pantograph for control design. Afterwards the real behaviour and the performance of the controlled pantograph can be determined by simulated line tests, carried out with a validated overhead line simulation program. For the control design of the ASP the simulation program PrOSA [2], which has been developed and validated with real line test data at the FTZ Munich for the last years, was used.

For the ASP a two-stage control circuit with the contact force as controlled variable has been realised.

The first stage, which works with the pneumatic driving mechanism already available, compensates very slow contact force fluctuations, e.g. caused by aerodynamic influences or by changes of the contact wire height at lowering sections. The closed loop control circuit ensures, that the mean contact force will stay in a defined, speed depending range. This mean, that a optimised mean contact force level can be specified for every pantograph in a train set separately. The influence of aerodynamic forces will be reduced and it will be possible to run on the overhead line under wear optimised conditions with a minimised, speed depending contact force level. The performance of the first control stage is limited by the pneumatic drive as well as by the first resonant mode of the pantograph overhead line system.

The electrically controlled pneumatic valve for the pneumatic cylinder of the driving mechanism is placed in the train. If the control system fails, it is possible to continue travelling - with reduced speed - by means of using the ASP with the normal passive pressure-regulation valve in this mode.
The pneumatic actuators of the second control loop are placed beside the two torsion bar springs at the pantograph head (see figure 2). The second control stage compensates the higher frequent contact force fluctuations, e.g. produced by the modulation over a span length or by the droppers. If the control circuit is activated, the movement of the actuators leads to a small rotation of the lever arms round the axis of the torsion bar springs and moves the contact strips, depending on the value of the output signal of the control circuit, up and down. As the pneumatic actuator system works up to a frequency of more than 30 Hz at the ASP head, contact force fluctuations will be reduced up to approximately 15 Hz.

A small cover protects the pneumatic actuators from rain, ice and snow and minimises the acoustical noise emission of the additional parts. The electrically controlled pneumatic valves are placed under a cover near the actuators on the top of the upper frame arm. The ASP also can be used without any control circuit in passive mode. In this case, the actuators of the second stage have no pressure and the contact strips will be fixed by the torsion bar springs only.

Used as controlled variable, the contact force is measured by four force and acceleration sensors, mounted between the contact strips and the contact strip holders. Based on the already existing contact force measurement system of DB AG, a miniaturised system has been realised [3]. As it was possible to reduce the necessary sensor electronic extremely, the electronic modules can be placed at the force sensors directly (see picture 3). The sensor modules generate digital output signals, which are, as far as possible, insensitive against electromagnetic influences.

On the base frame of the ASP a further electronic circuit for the conversion of the electrical signals into optical signals and the power supply of the sensors and actuators is placed. The optical signals will be transmitted via optical link from high voltage level to a computer at ground level in the train. The computer performs the signal analysis and the calculation of the control algorithm and generates the input signals for the actuators of both control circuits.

The electrical power supply for the electronic components of the ASP is designed as a stand-alone unit. A current transformer generates the necessary electrical energy from the actual current flow to the train at high voltage level. This energy is used to charge an accumulator, which is placed in the electronic circuit on the ASP base frame.

### 3 Actual results

Up to day two prototypes of the ASP, an active type and a passive type without actuators and sensors, have been built up. They have been tested in a wind tunnel up to a speed of 300km/h for the first time. Furthermore the transfer characteristics of the sensor and actuator systems of the second control circuit have been checked at the pantograph test bench.

A prototype of the ASP head already was build up in the last year. The prototype head was mounted on the upper frame of a DSA350SEK construction. Completed with actuators and sensors of the two-stage control circuit, this test assembly could be used for examinations of the design and the installation of the actuators and sensors before the ASP-prototype was produced completely. With the test assembly model parameters have been derived from identification measurements at the
pantograph test bench. Simulations studies have been carried out for control design and determining the system performances.

Wind tunnel tests

Wind tunnel tests with the two ASP prototypes and a DSA350SEK pantograph for reference have been carried out at the Audi wind tunnel in Ingolstadt. The tests should demonstrate the acoustical performance of the ASP in comparison to the SEK-type and should give information about further improvements for the ASP design.

The examinations were made for different speed levels up to 300 km/h at the lowering position of the pantographs and at a working height of 1.6 m for both driving directions. For the acoustic measurements single microphones and a new microphone array of the FTZ with 89 microphones have been used.

Additionally the aerodynamic uplift force of the pantographs were measured via two force sensors, mounted on the base frame of the pantographs and connected with the contact strips by thin cables.

At a speed of 300 km/h the noise emission of the ASP was approximately 4 dB(A) lower than the emission of the SEK-pantograph. There was no significant difference between the active and passive ASP-type. Figure 4 shows the result of the array measurement for the ASP (active) and the SEK-pantograph at a speed of 300 km/h. The SEK has a dominant noise emission at the pantograph head, whereas the ASP-noise emission dominates in the area of the base frame.

Measurements of the ASP without the pantograph head have shown only small reduction of the noise emission. This may be the result of the very dominant noise emission of the base frame. This means, the ASP head has already a suitable design, significant noise sources are localised at the base frame. Examinations with a simple cover in front of the ASP base frame have confirmed these results. The noise emission of the ASP could be reduced significantly by this cover. Till the next wind tunnel tests Bombardier Transportation will realise a optimised cover for the base frame.

As result of the greater diameters for single parts of the ASP construction the resulting aerodynamic uplift force of the ASP is nearly twice of the uplift force of the SEK. The force distribution between both contact strips was not satisfactory, too. This means, that the ASP needs – like the SEK - additional aerodynamic vanes at the upper frame for correcting the mean contact force and at the contact strips for improving the force distribution.

Examinations of a ASP prototype head at the pantograph test bench

A prototype of the ASP-head, mounted on a SEK pantograph, was examined in very different ways at the pantograph test bench of the FTZ [4]. Aim of the examinations was to find suitable
pneumatic actuators and electrically controlled pressure valves for the use at the ASP head and furthermore possibilities for the integration of the actuators at the ASP construction. Therefore the transfer characteristics of the controlled system have been measured and analysed for different configurations with several actuator systems under different operational conditions. The measured transfer functions have been taken as input data for the identification of reliable parameters for modelling the ASP. The validated ASP models were used for control design and the simulation of the interaction with different overhead line systems.

Figure 5 shows the well correspondence of measured and simulated transfer functions of the second control stage circuit as relation of the resulting contact force respectively the signal of the force sensors (without acceleration correction) as functions of the input signal of the electrically controlled pressure valves. The dominate resonance mode at 5Hz results from a simple mass-spring-system, which is used for the approximation of the catenary at the pantograph test bench. It is possible to move the contact strips and influence the contact force up to more than 20 Hz with an adequate change of the phase in the controlled system by pneumatic actuators. Examinations with small pneumatic bellows instead of linear cylinders have shown comparable results. Bellows have advantages especially concerning life time, temperature range, weight and mounting at the ASP head.

Actual measurements with the ASP-prototype have shown no significant differences between the transfer characteristics of the ASP prototype and the test assembly with the ASP prototype head mounted on the SEK.

**Simulation**

For the development of controlled pantographs, simulation studies with a validated overhead line simulation program are indispensable. For the ASP, simulated line tests with the overhead line simulation program PrOSA and validated multiple-mass models of the ASP prototype head, mounted on a SEK pantograph have been carried out. The simulation results give information about the
behaviour and stability of the closed loop control circuit in contact with the overhead line system as well as the performance of the controlled ASP. In comparison with the passive SEK-pantograph the contact force fluctuation will be reduced up to 20Hz by the control circuit (see figure 6). The maximum contact force will be reduced for approximately 50 N, the minimum contact force will be lifted up for 30 N and the standard deviation decrease from 25 N for the SEK to 15 N for the ASP. This means an improvement of contact force fluctuation of more than 40%.

The intended line tests will show, if this noticeable improvement will be reached at the real overhead line system, too.
4 Outlook

The results of wind tunnel tests with the ASP prototype and simulated line tests with a validated model of the controlled ASP head have shown that it is possible to reach the defined aims with the ASP.

Actually measurements at the pantograph test bench will be carried out to identify the system behaviour of the controlled ASP-prototype and get relevant parameters for the control design. The adjustment of the closed loop control circuit should be finished till September and - after a final check of the functions of the active systems and the whole ASP at the test bench - line tests will be carried out at the following months.

A second wind tunnel test should be realised in November. Till this time, the optimisation steps to improve the noise emission, for instance by an additional cover of the base frame, should be realised. Finally the reduction of noise emission should be proven by measuring the pantograph noise behind a sound barrier on the track.

Even if all the results will be positive, further activities are necessary in order to optimise the actuators, the sensors and the electrical systems for the difficult environmental and operational conditions on the roof of a train. After this optimisation step the standardisation of the ASP can be started and some ASP’s could be tested under normal operational conditions over a period of one year.

Bibliography

[1] Low noise pantograph ASP – recent developments;
W. Behr, T. Lölgen, W. Baldauf, L. Willenbrink, R. Blaschko, K. Jäger, J. Kremlacek;
Inter.noise 2000, Nice, France

[2] Validated simulation tools for reliable investigations of the catenary-pantograph interaction;
T. Schulze, W. Baldauf, G. Poetsch; WCRR 2001

[3] Compact contact force measurement system – online diagnosis of the overhead line system with regular trains
M. Kolbe, W. Baldauf, WCRR 2001

J. Deml, W. Baldauf; WCRR 2001

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