Mathematical Modelling of Smooth and Precise Adaptive Train Braking System

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Keywords: Adaptive Systems, Intelligent Control, Railway Transport Braking Systems, Modelling.

Abstract: This position paper provides a new insight into the smooth and precise adaptive railway transport braking system design. The first phase of the development is described and includes a development of a necessary mathematical and computer model. Components of new adaptive braking system and their interactions are defined. Mathematical model contains equations that describe the movement of the train and the pneumatics braking system of the train, as well as offering new features of the developed system, which will adaptively adjust the service brake modes and will perform real-time system diagnostics without any human interaction. The computer model and simulation results are described in this position paper.

1 INTRODUCTION

Nowadays the industry of railway transport is developing new solutions for increasing a capacity and speed of the railway. These actions are followed by various problems that connected with railway transport movement safety, which has to be at least at the same or higher level than before (Wang, Wang et al., 2012).

Authors are solving the safety problem and propose to develop new smooth and precise adaptive braking system of the rolling stock. This new system is aimed to reduce various deficiencies of existing railway safety systems. The purpose of the system is an automatic braking of the rolling stock using service braking and previously developed safety functions (Gorobecs, Greivulis et al., 2009), which allow to stop the train before another railway vehicle, before a level-crossing where a road vehicle is stuck or before the signal with restrictive aspect. Usage of emergency braking has negative effect and not recommended if regular service braking might be performed. Therefore, the new proposed system is based on authors' previously developed railway safety systems and may increase safety level of the train and the railway system as a whole.

After real field test experiments (Potapovs, Gorobetz et al., 2012) authors concluded that efficiency of the previously developed railway safety system is not sufficient, because the system does not adapt to various working environment conditions and may work imprecise if the rolling stock contains various wagons.

Therefore, the research and development of new smooth and precise adaptive train braking system, which is now patented (Potapovs, Levchenkov et al., 2013), is going on. This process contains some development stages and the first one is described in this paper.

2 PURPOSE AND TASKS

Main goal of the research is to develop a new smooth and precise train braking control system based on adaptive algorithms and neural networks.

Main tasks for the goal achievement are following:

1) Development of the mathematical model and the computer model of train movement and work of the pneumatics braking system;
2) Development of the adaptive control algorithm using neural networks, for the new braking control system, based on the developed mathematical un computer models;
3) Simulation of self-organization of the adaptive braking control system using developed algorithms;
4) Development of prototypes of the new adaptive braking control system, testing in laboratory conditions and performance of field tests.

Potapov A., Gorobetz M. and Levchenkov A..
Mathematical Modelling of Smooth and Precise Adaptive Train Braking System.
DOI: 10.5220/0004592602040209
In *Proceedings of the 3rd International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2013), pages 204-209
ISBN: 978-989-8565-69-3

In this paper the mathematical model and the computer model of train movement and pneumatic braking system is described.

3 PRINCIPLES AND NOVELTY OF NEW SMOOTH AND PRECISE ADAPTIVE TRAIN BRAKING SYSTEM

Main functions of the new smooth and precise adaptive train braking system are following:

- Automatic train stopping in a target point using regular service braking modes;
- Definition of the target point according to existing routing data, such as a stop at the defined platform point, or to safety reasons, such as a risk of collision or a risk of trespassing the restrictive signal aspect;
- Real-time diagnostics of train pneumatic braking system during the operation and self-learning for precise braking;
- Sending alarms to the driver about possible failures of a train pneumatic braking system.

Advantages of the new smooth and precise adaptive train braking system using are following:

- The system does not disturb work of existing pneumatics braking system;
- The system does not disturb a train driver to perform his duties and no manual input is needed from the driver;
- The system does not need the installation of additional embedded sensors, because it would cause the reconfiguration and recertification process.

Main components of the braking system of the train and the adaptive braking control system are divided in four groups.

The first group contains pneumatics elements of the existing braking system (Fig. 1. shown in blue):

- Compressor (K);
- Main reservoirs (GR);
- Driver's control valve (MK);
- Electropneumatic valve (EPV);
- Feeding main line (BM);
- Braking main line (BrM);
- Compressed air relay (GSR);
- Air splitters (GS);
- Braking cylinders (BC).

The second group contains proposed mechanical elements of new braking control system (Fig. 1. shown in yellow):

- New connections of braking main line;
- High-pressure tubes and flexible connectors;
- Electropneumatic valves (V1 and V2);
- Analogue electrical manometer (AMN);
- Protective valve (DrV) to control pressure at maximum allowed level;
- Emergency valves (AV1 and AV2) used in emergency situation to shunt specific parts of braking main line.

The third group has electronic components and electric extension modules: (Fig. 1. shown in olive green):

- Programmable logic controller (PLC), which performs main calculation and control functions;
- Input/output modules for devices (IM);
- Power supply unit (BB);
- Wireless communication module (BSM);
- Satellite positioning module (GPM);
- Driver interface module (IIM).

From the one side PLC usage in this case needs to meet requirements of various railway safety standards such as EN 50126, EN 50128, EN 50129. From the other side usage of programmable devices in many years proved its workability in different fields and safety systems and provides great possibilities for improvement of the system functionality.

The fourth group contains software components of the PLC:

- Initialization function;
- Satellite global positioning system data processing function;
- Wireless communication function;
- PLC input/output control functions;
- Adaptive control function based on neural networks – realizes self-learning of control system by analysing of the train braking system and performs control of the system.

Figure 1 provides the principle scheme of the new smooth and precise adaptive train braking system integrated in existing braking system.

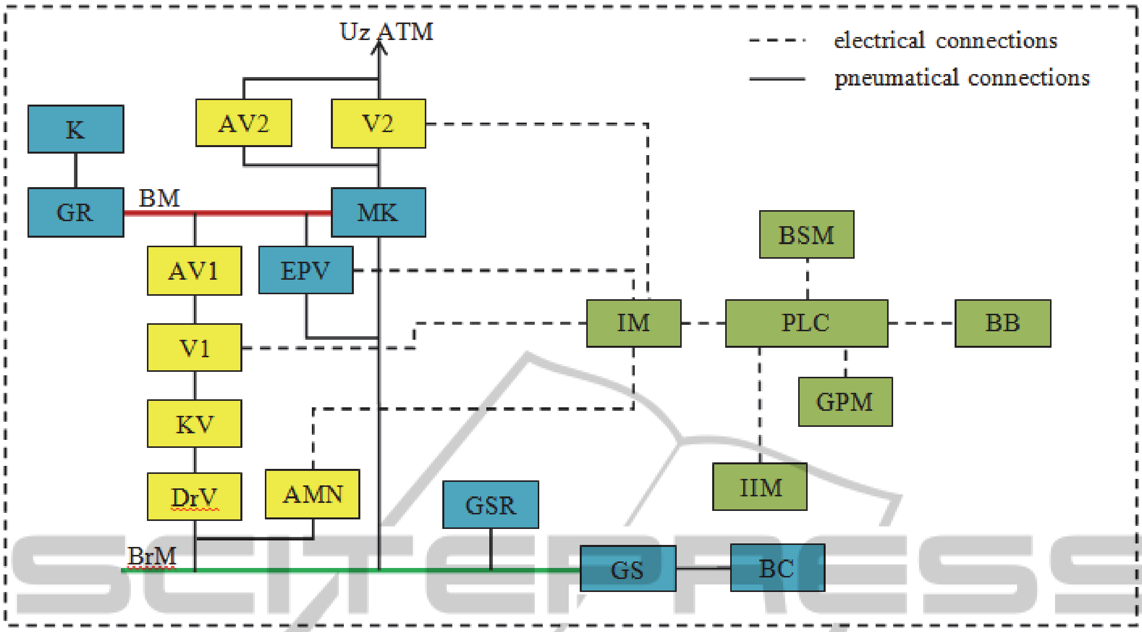

Figure 1: Main nodes of new smooth and precise adaptive train braking system.

4 MATHEMATICAL MODEL OF TRAIN BRAKING SYSTEM NODES

In the first approximation of train movement and pneumatics model, the rolling stock is considered as whole moving object without wagon details. This step allows removing uncertainties of various wagon types, cargo load and different braking modes of individual wagons. But in spite of such simplification, increasing of the longitudinal loads of train and other factors influencing the activity of brake system should be taken in account.

Following equations are proposed to use for simplified train movement mathematical model. Taking in account that the train is moving, the train deceleration a_{br} may be calculated as following:

$$a_{br} = \frac{F_{brak} + F_{frict}}{m}, \quad (1)$$

where, Fbrak – braking force of train pneumatic braking system, N;

Ffrict – train friction force, N;

m – mass of whole train, kg.

From the literature (Shuleshenko, 1985) we know that other forces influences movement of the train, but as these forces are variable, uncontrollable and minor, it is proposed to use the most important of them.

Train friction force F_{frict} is calculated using train movement specific resistance ω_0:

$$F_{frict} = \omega_0 \cdot m \quad (2)$$

where m – mass of the train, t.

The specific resistance of train movement ω_0 defined by equation:

$$\omega_0 = \omega_x + \omega_0^{"} . \quad (3)$$

The specific resistance of the locomotive ω_x defined by the formula:

$$\omega_x = 2{,}4 + 0{,}009V + 0{,}00035V^2 . \quad (4)$$

But the specific resistance of wagons $\omega_0^{"}$ calculated by formula:

$$\omega_0^{"} = 0{,}7 + \frac{8 + 0{,}1V + 0{,}0025V^2}{q_0}, \quad (5)$$

where V – speed of train, km/h;

q_0 - axle load.

Formulas defined for long-welded track and taking in account that rolling stock contains four-axle cargo wagons with axle load more than 6 t (during the simulation it is possible to use another equations, describing another track type or wagons).

The braking force of the rolling stock Fbrak may be defined by known train specific braking force B_T:

$$F_{brak} = B_T \quad (6)$$

Specific braking force B_T is calculated using the equation:

$$B_T = 1000 \cdot K_{calc} \cdot a \cdot b \cdot n \cdot \varphi_{calc}, \quad (7)$$

where K_{calc} - rated pressure force to one slipper;

a – number of slippers at one axle;

b – axle number in a wagon;

n – number of wagons in a rolling stock;

φ_{calc} - rated friction coefficient of a slipper.

Braking coefficient ν_{apr} shows the proportion of total slippers pressure force to the mass of the rolling stock. A lot of parameters are needed to calculate ν_{calc} (Shuleshenko, 1985) and it is impossible to get the values of these parameters without additional data input. Therefore, the value of these parameters should be defined as minimally allowed value before adaptive self-learning.

By the model φ_{calc} is calculated by equation:

$$\varphi_{calc} = 0{,}27 \cdot \frac{V + 100}{5 \cdot V + 100} \quad (8)$$

As the pneumatic braking system of the rolling stock is going through the whole length of rolling stock is has working inertia, rated pressure force K_{calc} can not be set as the same maximum value at the moment when the braking mode is activated. According to the distribution (Vencevich, 2006) approximation of pressure force along the rolling stock the equation for a percentage of full $K_{calc\%}$ is got:

$$K_{calc\%} = -1{,}55 \cdot K_{calc}^{\;2} + 28{,}28 \cdot K_{calc} - 30 \quad (9)$$

Similar process happens when releasing the brakes after full service braking. The value of K_{calc} reduces from its maximum to zero in 35-38 s in the first wagons of the train and in 55-60 s in the last wagons of the train.

Minimal allowed value of coefficient ν_{calc} in cargo train is 0,33 (Vencevich, 2006). But it is necessary to calculate the precise value of this parameter to perform precise and smooth braking control.

Therefore, the main task for adaptive system and neural network is a detection of the braking coefficient ν_{apr}. It must be calculated automatically during the train movement.

For this case, authors propose to input a new parameter in the model – coefficient of train braking system efficiency BS_{ef}.

This coefficient is defined by following functional dependency:

$$BS_{ef} = f(\Delta P; \Delta V; i; t_{brak}, t_{stab}), \quad (10)$$

where, ΔP - changing of the air pressure in the braking main realizing one braking step

ΔV – changing of the railway transport speed realizing one braking step;

i – slope of the track profile, %;

tstab – time of stabilisation of braking system pressure;

tbrak – braking time, s.

A parameter ΔP defines pressure changes in braking main line from initial value to stabilized value after braking starting.

$$\Delta P = | \; P_1 - P_0 \; | = const, \quad (11)$$

where P1 – pressure in a braking main line after the braking step;

P0 – pressure in a braking main line before braking.

Stabilization time tstab depends on a selected braking mode and various factors such as leakage in braking system, length of the rolling stock, outdoor temperature etc.

For calculation of ΔV parameter initial speed V0 and speed after braking step V1, when $\Delta P = const$.

$$\Delta V = | \; V_1 - V_0 \; | \quad (12)$$

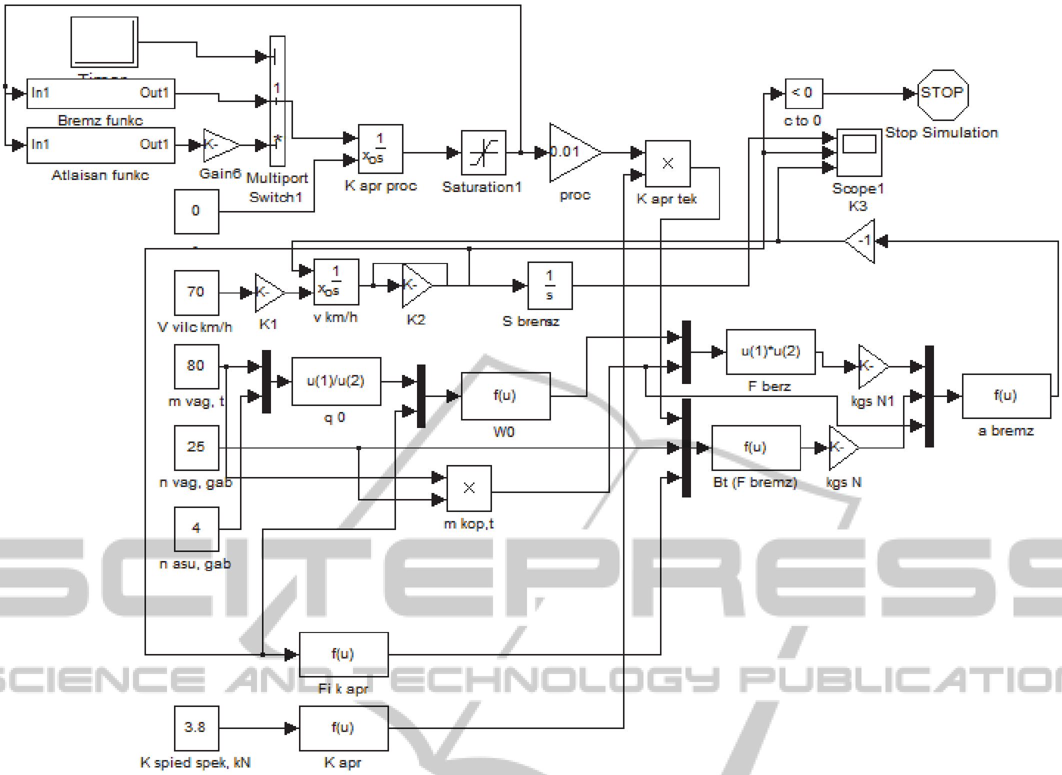

Figure 2: Computer model of train braking system behaviour.

Slope may be received from the database in PLC memory.

The theoretical braking distance using service braking may be calculated after the calculation of the coefficient of train braking system efficiency.

$$S_{br} = f(BS_{ef};T_{out};V_{train},i) \qquad (13)$$

where T_{our} – outdoor temperature, which has influence on cohesion between wheels and rails, $^{\circ}C$;

V_{train} – train movement speed, km/h.

Using S_{br} it is possible to calculate point at which automatic service braking must be started to stop the train in the target point.

Outputs of adaptive algorithm and neural network should be time moments when braking and release of braking is necessary. Calculation of theoretical curves and obtained data about the pneumatic braking system during the train movement will be the base of calculation. The following constraints must be taken in account:

- Maximum braking time;
- Planned time for P_1 achievement (braking and releasing brakes);
- Train speed V_{train};
- Train physical parameters (longitudinal loads in the rolling stock);
- Outdoor temperature influencing cohesion and pressure change time.

5 COMPUTER MODEL OF TRAIN BRAKING

The first approximation of the computer model of train braking system behaviour is developed in Matlab/Simulink environment and shown in Figure 2. The computer model allows setting up following initial parameters:

- Train speed V, km/h;
- Mass of one wagon, t;
- Number of wagons, n;
- Pressure force of braking slippers K, N/t;
- Function of $K_{calc\%}$ increasing and decreasing according to the train length.

The model contains realization of two service braking modes: braking mode and release mode. For these modes function „Bremz funkc" un „Atlasan

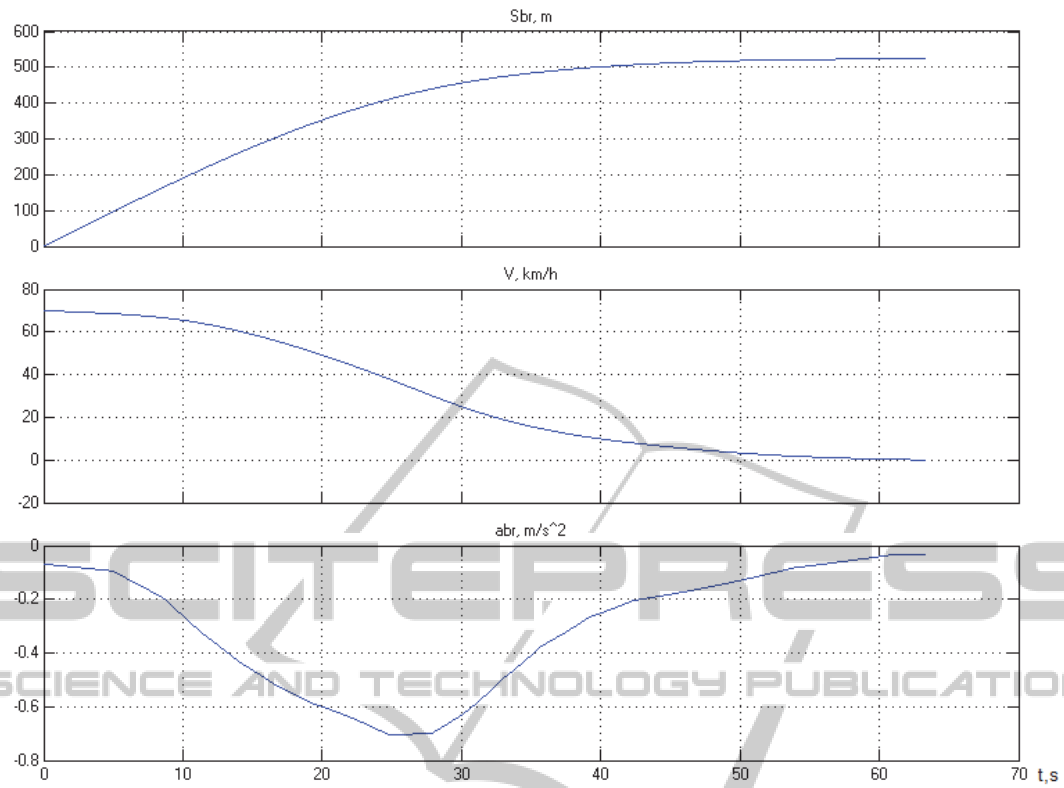

Figure 3: Computer model simulation results.

funkc" are developed.

Graphical simulation results are representing the case of braking the rolling stock with a mass 2000 t from initial speed 70 km/h and release brakes at 25th second. The total length of the braking way is 523 m and braking time 63 seconds.

6 RESULTS AND CONCLUSIONS

Following results are achieved:

- The mathematical model is created for train service braking modes;
- The computer model is created for simulation of train behaviour when breaking and releasing brakes;
- Graphical simulation results obtained.

Developed mathematical model of smooth and precise adaptive braking control in the first approximation allows creating the computer model, which is precise enough to get reliable simulation results. Reliability of obtained results has been checked by theoretically and practically obtained data described in the literature.

Further stages of smooth and precise adaptive train braking control system development will be presented in next publications.

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