Automatic target adjusting braking of a shunting stock with an adaptive control law

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Abstract. The article deals with the problem of automation of target adjusting braking of a shunting stock. It is proposed to build it on the basis of an adaptive control algorithm capable of functioning under the current uncertainty of the parameters of the control object. It is based on a scheme with a current parametric identification assigned by an implicit reference model and using “simplified adaptivity conditions”. For the synthesis of the control, the approach implemented in a standard locomotive system for automatic braking control to maintain the target speed of movement depending on the distance to the target point is used. The results of simulation modelling are presented.

1. Introduction

When carrying out shunting work, it sometimes happens that the pneumatic brakes of the coupled wagons are not connected to the shunting locomotive or are partially connected. At the same time, the governing documents require that the speed be limited by 60, 40, 25, 15, 5, 3 km/h [1]. Of course, in order to reduce the time for shunting movements, the speed of consist must be close to the indicated values. In this regard, the Locomotive Engineer must maintain the target speed in sections and target adjusting braking, which are currently performed manually. Due to the significant inertia of the air brakes of coupled cars (even if they are connected to a diesel locomotive), locomotive engineers often use locomotive brakes: either a rheostatic or an air auxiliary brake. Otherwise, using car brakes, you can completely slow down the shunting stock with an undesirable loss of time. Inexperienced locomotive engineers often make mistakes in this case.

There is a problem of automating the target adjusting braking of a shunting stock when the locomotive brake is used. And since this is controlled in a priori uncertain conditions (the weight of the cars, the degree of the track slope, the state of the brakes, etc.), this automating is proposed to perform at an adaptive level that provides for achieving the target with the current uncertainty of the parameters of the control object. This is the problem this article is focused on. An air brake of a diesel-electric locomotive will be considered.

2. Mathematical model of braking

As an adaptive control law that can be adapted to the current parameters of the controlled object is considered below, it is enough to discuss design concept using the example of one wheelset of a diesel-electric locomotive with averaged parameters in the braking mode is enough to be discussed. A description of the properties of the indicated wheelset of a locomotive can be considered on the basis
of figure 1, which is a side view of a wheelset on a rail with a locomotive mass attached and referred to it and an acting force from the cars.

![Mathematical model of braking of a shunting stock reduced to one wheelset of a locomotive.](image)

Figure 1. Mathematical model of braking of a shunting stock reduced to one wheelset of a locomotive.

The figure shows: \( m_l, m_c \) is the mass of the locomotive body and cars, respectively, referred to one wheelset, is determined by the total mass of the locomotive body and cars by dividing by the number of wheelsets of the locomotive; \( m_w \) is the mass of the wheelset; in the following, denote \( m = m_l + m_w \); \( \rho \) is the track slope angle; \( V \) is the linear speed of the center of the wheelset (linear speed of the shunting stock); \( F_p, F_{br}, F_{ext} \) is the pressure force on the brake block, the braking force and the external force, respectively, referred to one wheelset in a manner similar to the above.

It is known that the braking force of a pressure brake is determined by the dependence (taking into account that usually a wheelset of a locomotive has 4 brake blocks):

\[
F_{br} = 4\phi(V, F_p)F_p
\]

where \( \phi(V, F_p) \) is the coefficient of the brake block, which nonlinearly depends on the speed and force of pressing on the brake block. The dependence \( \phi(V, F_p) \) for each type of brake blocks is well studied and is presented in [2] in the form of an approximate dependence.

The pressure force applied to the brake block is formed by the locomotive engineer's control signal in the form of turning the handle of the auxiliary brake crane or the signal of the automatic control system being designed with a delay associated with switching, filling and releasing air from the brake cylinders, etc. Thus, the model of signal transmission from the locomotive engineer or the control system can be simulated as:

\[
F_p(t) = k_u u(t - \tau)
\]

where \( t \) is the current time, \( k_u \) is the proportionality coefficient, \( u(\cdot) \in 0 \pm 1 \) is the control signal for braking; \( \tau \) is latency.

Let us assume that the generated braking force is fully provided by the wheel-rail adhesion force, i.e. there is no wheelset jamming when braking. It is believed that this is ensured by additional measures, for example, limiting the weight of the shunting stock, limiting the maximum pressure on the brake blocks, etc.

Let us also assume that the external force is generated by the slope of the track and the resistance to the movement:

\[
F_{ext} = m_c g \sin \rho - W_t - W_c
\]

where \( m_c = m_l + m_c \); \( g \) is the free fall acceleration; \( W_t, W_c \) is the resistance to movement from the locomotive and cars, respectively, referred to one wheelset of the locomotive; \( W_t, W_c \) are functions of the mode of motion and speed and are described, taking into account the accepted designations, in the form of polynomials [2]:
\[ W_1 = (a_{l0} + a_{l1}V + a_{l2}V^2) m_l; \quad W_c = \left[ a_{c00} + \left( a_{c10} + a_{c11}V + a_{c2}V^2 \right) / q_c \right] m_c, \]

(4)

where \( a_{l0}, a_{l1}, a_{l2}, a_{c00}, a_{c10}, a_{c11}, a_{c2} \) are constant coefficients; \( q_c \) is the part of the weight of the car applied to one of its axles.

Taking into account the equation of the train motion [3, 4], the adopted definitions and figure 1, it can be written:

\[ m_c (1 + \gamma) V = -F_{br} + F_{ext}, \]

(5)

where \( \gamma \) is the coefficient of inertia of accelerating masses.

There is an objective for the function of target adjusting braking in a specific situation: to reduce the speed from value \( V_0 \) to value \( V_1 \) on a set track \( \Delta S \), starting from the current position.

This problem can be solved by using the approach implemented in the standard automatic brake control system (ABCS) located on most modern locomotives (it is not used in shunting modes of locomotive operation), where tracing the target braking trajectory in the form of a dependence \( V_{tgt}(S) \) with boundary values \( V_0 \) and \( V_1 \), \( S \in \Delta S \) is the distance to the end of the braking section, to the designated target point. Indeed, ABCS solves the problem of complete braking when \( V_1 = 0 \). But due to the fact that when brakes are controlled by ABCS, as a rule, “outdated” data from testing the brakes is used, and not the current one, the inaccuracy of such target braking can reach \( 100 \) m [5]. This is unacceptable for many shunting operations.

From the equality of the difference between the kinetic energy of the train at the ends of the braking section and the work of the braking force, considering the other types of energy consumption and generation to be zero and the slope angle of the track to be zero, an equation for a set braking trajectory can be derived and its parameters are determined. So, if constant acceleration of braking is created in the form:

\[ a_{br} = -\left( V_0^2 - V_1^2 \right) / (2 \Delta S), \]

(6)

then during braking action

\[ t_{br} = (2 \Delta S) / (V_0 + V_1), \]

(7)

the problem will be solved. The target braking trajectory corresponds to equalities (6), (7):

\[ V_{tgt}(S) = \sqrt{V_1^2 + \left( V_0^2 - V_1^2 \right) S / \Delta S}, \]

(8)

An example of a diagram \( V_{tgt}(S) \) with parameters: \( V_0 = 8.3 \text{m/s (30km/h)}, V_1 = 1.4 \text{m/s (5km/h)}, \Delta S = 200 \text{m}, a_{br} = 0.17 \text{m/s}^2, t_{br} = 41.2 \text{s} \) is shown in figure 2.

![Figure 2. The target braking trajectory.](image-url)
If the actual speed of the shunting stock is ensured to be equal to the target one, then the set objective of target adjusting braking will be solved even in conditions different from the problem formulated above. Of course, the latter will change the dependencies (6) and (7).

3. Synthesis of the control law

The control system configuration with the current identification algorithm, an implicit reference model and “simplified adaptability conditions” will be used to synthesize the law of adaptive braking control as a solution to the problem with current parametric uncertainty [6, 7].

Based on (1) – (4), we write the equation of motion of the shunting stock instead of (5):  

\[
\dot{V}(t) = \frac{g \sin \rho}{1 + \gamma} \left[ a_{10} m_h + a_{c00} m_c + a_{c01} m_c \right] + \left[ a_{11} m_h + a_{c1} m_c \right] V(t) + \left[ a_{12} m_h + \frac{a_{c2} m_c}{q_c} \right] V(t)^2 - \frac{4 \varphi(V, F_p) k_u (t - \tau)}{m_c (1 + \gamma)} - a_0(V) + a_1(V) W(t) + b(V, F_p) u(t - \tau),
\]

where \( a_0(V), a_1(V) \) are coefficients depending on the speed, such that the expression \( \left[ a_0(V) + a_1(V) W(t) \right] \) approximates on the current sliding time period of identification the quadratic dependence on the speed, represented by the first two summands of the first part (9); \( b(V, F_p) = -4 \varphi(V, F_p) k_u \left[ m_c (1 + \gamma) \right] \).

The path to the end of the braking section \( S \) is determined by an obvious relationship:  

\[ S(t) = \Delta S - \int_{t_0}^{t} V(t) dt, \]

where \( t_0 \) is the start of braking.

An implicit stable reference model is assigned corresponding to the aperiodic link [8] to formalize the requirements for braking properties:

\[
\dot{V}_m(t) = a_m \left( V_m(t) - V_{tgt}(S) \right), \quad V_m(t_0) = V_{tgt}(\Delta S), \quad V_0 \geq V_{tgt} \geq V_1,
\]

where \( V_m \) is the model behavior of the speed of the shunting stock; \( a_m \) is a selected negative parameter of the standard, which determines the dynamics of the properties of a closed control system to the properties of the reference model; \( V_{tgt}(S) \) is the calculated target braking trajectory by (8).

If the parameters of the object (9) were a priori known and the delay in (2) was zero, then the control law that would provide identity of the behavior of a closed control system and reference model: \( V \equiv V_m \equiv V_{set} \), is determined by the formula (accurate law):

\[
u^*(t) = b(V, F_p)^{-1} \left[ \left( a_m - a_1(V) \right) V - a_0(V) - a_m V_{tgt}(S) \right],
\]

It is easy to check by substituting this control law in (9). Since the parameters are unknown, then instead of (12) the law built on the current estimates of unknown parameters (the upper symbol “ \( \hat{\} \) ” indicates estimates of the corresponding parameters) is formulated:

\[
u(t) = \hat{b}(V, F_p)^{-1} \left[ \left( a_m - \hat{a}_1(t) \right) V(t) - \hat{a}_0(t) - a_m V_{tgt}(S) \right],
\]

Current estimates are proposed to be determined using the recurrent method of smallest squares with a forgetting factor [9]:

\[
\hat{\theta}_t = \hat{\theta}_{t-1} + P_t y_t e_t; \quad e_t = z_t - y_t^T \hat{\theta}_{t-1}; \quad P_t = P_{t-1} - P_{t-1} y_t y_t^T P_{t-1} \left( 1 + y_t^T P_{t-1} y_t \right)^{-1} \beta; \quad P_0 = \beta E_2; \quad \beta < 1.
\]
where the index $i = 1, 2, 3, ...$ indicates the discrete moments of time in step $\Delta t$; $\hat{\theta}_i = [\hat{a}_{0i}, \hat{a}_{1i}]^T$ is the vector of the desired estimates; top index “$\hat{\cdot}$” means transposition; $y_i = [1, V]^T$ is the vector of regressors corresponding to the desired estimates; $e_i$ is the residual of identification; $z_i = \hat{V}_i + \hat{b}u_i - \epsilon_i/\Delta t$
is the response of the object; the estimate $\hat{b}$ will be approximated by a priori information by virtue of its presence and properties of a closed adaptive control system built on “simplified adaptability conditions”, see (15); $P_j$ is the matrix coefficient of amplification of the algorithm $(2 \times 2)$; $\beta \rightarrow 1$ is the assignable “forget factor”; $\theta$ is a large positive number; $E_2$ is the identity $(2 \times 2)$ matrix.

“Simplified adaptability conditions” require that the estimate $\hat{b}$ have the properties [6, 7]:

$$\text{sign}(\hat{b}) = \text{sign}(b); \quad |\hat{b}|/2 \leq |\hat{b}| \leq |\hat{b}|_{\text{max}}; \quad \frac{|\hat{b}|_{\text{max}}}{\hat{b}} \geq 2; \quad d\hat{b}/dt \rightarrow 0,$$

(15)

and the residual of identification sought to zero that the algorithm (14) is sufficiently “easily” perform.

In addition, the control law (13) will be “not sensitive” to the delay in the control system ($\tau \neq 0$), if the identification algorithm (14) provides estimates with fairly good predictive properties for a period of ahead. The method of the smallest squares has this property.

It is advisable to use the estimate $\hat{b}$ in the form of its value calculated under a priori data and exclude it from the identification procedure, as implemented in the algorithm (14). Due to the determination of the parameter by (9), its estimate can be approximately calculated, since the dependence $p(V, F_p)$ for specific types of pads is approximately described in [2]. Parameters $k_u, m_2, \gamma$ are also approximately known.

The signals $\hat{V}, V, S$ must be measured for implementation of the control law (13) and the identification algorithm (14). They are available on modern locomotives [10].

4. Example

Let us consider a typical shunting stock with diesel-electric locomotive TEM18DM: 6 wheelsets; the mass of locomotive referred to one wheelset is $m_1 = 126 / 6 = 21t$; brake blocks are made of cast iron [11]. The rest of the shunting stock is 10 four-axle gondola cars for 80t each. Hence parameters: $m_c = 800 / 6 = 133t$, $q_c = 80 / 4 = 20t$.

The calculated pressure force on the cast-iron brake block in loaded mode is 110 kN [2, 11]). Take this value as the maximum for $F_p$, then $k_u = 110kn$. The delay time is taken as $\tau = 1.5s$, considering that it corresponds to the current braking mode. The friction coefficient of cast iron blocks is determined by [2]

$$\varphi = 0.6 \left[ (1.6F_p + 100)(V + 100) \right] / \left[ (8.0F_p + 100)(5V + 100) \right],$$

(16)

where $\varphi$ is a dimensionless coefficient, $F_p$ is measured in kN, and $V$ is in km/h.

The parameters of equation (4) correspond to the movement of a locomotive with an electric traction at idle mode and four-axle gondola cars [2]:

$$a_{10} = 23.5N/t, \quad a_{11} = 0.11(N/t)(h/km), \quad a_{12} = 0.0034(N/t)(h^2/km^2),$$

$$a_{100} = 5.2N/t, \quad a_{110} = 35.4N, \quad a_{120} = 0.785h/km, \quad a_{22} = 0.027h^2/km^2.$$

(17)

The inertia coefficient of rotating masses in equation (3) will take equal to $\gamma = 0.06$, which corresponds to its estimated value for standard cases of freight trains [3, 4]. The gradient angle will be:
\( \rho = 0.11^\circ \), which corresponds to approximately \( 2^\circ/\infty \). As an objective of target adjusting braking, we will take the above objective with target braking trajectory according to figure 2.

The simulation was carried out in Matlab environment with the implementation of the model of motion of the shunting stock described by (1) – (5), (10), (16), (17) and with the above parameters.

For the reference model (11), the following is assumed: \( a_m = -1 \text{s}^{-1} \). The parameters of the identification algorithm (14): \( \Delta t = 0.3 \text{s} \) (with this temporary step, the control law was also calculated (13)), \( \theta = 10 \), \( \beta = 0.98 \). The estimate \( b(V, F_{p}) \) was calculated from dependencies (9), (16), taking into account a priori information about the parameters \( k_u, m_C, \gamma \). Since the latter are known from the model being used, the estimate obtained is \( \hat{b}(V, F_{p}) = b(V, F_{p}) \). To simulate the inaccuracy of data in practice, the resulting estimate was multiplied by a coefficient in the range \( 1.5 \div 3 \), corresponding to (15). In the example below, this coefficient is 2, other values of this multiplier from the specified range, as well as the constant value of the assessment \( b \) of this range, do not yield any practical differences in the behavior of a closed control system.

Figure 3 shows the simulation results for the specified conditions. In this and other figures, the target speed is indicated in gray. This figure shows that braking occurs approximately in 40s, the actual speed is close to the target value throughout the interval of braking. Figure 4 shows the dependences of the actual and target velocities from the variable \( S \). Almost the same results are obtained under the same conditions, but with one car in the shunting stock, only the control action is approximately 10 times less. Inaccuracy of reaching the speed at the end of the braking section is within 0.4 m/s (1.4 km/h).

5. Conclusion
Model studies of the proposed system of adaptive control of target adjusting braking using a locomotive air brake show its sufficiently high accuracy in comparison with similar standard systems. The specified algorithm could be used in a design of a similar system using rheostat braking of the locomotive. The proposed system can be constructed using modern microprocessor hardware and integrated into existing locomotive control systems. The system can also be considered as a subsystem of a promising complex for autopilot guidance of a shunting stock.
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