Models of Locomotive Traction Drives for the Improvement of Sand Feeding System

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Abstract. In this research, we calculated the key characteristics and parameters of the pneumatic injector using the set input and output gas flow values. We simulated the ejection of excessive air from the ambient to increase the flow rate of the air-and-sand mixture from the outlet chute of the sand feeding system of a locomotive using the CFD package of the FlowSimulation extension of the SolidWorks solid object design environment. We achieved the reduction of the compressed air consumption as compared to the standard locomotive sand-feeding systems.

1. Introduction

Many different commercial locomotives for main railway lines feature class I traction drives with support-axle-suspended direct current series-wound traction electric motors (TEM). These electric devices became widely popular because of the simple adjustment of spinning rate and ‘soft’ hyperbolic traction parameters, which allows maintaining the levels of power consumption across at any speeds and utilize maximum traction torque when starting from a standstill that decreases as the speed grows.

However, this type of drive is prone to excessive wheel sliding and stalling under harsh operating conditions, such as the operation on greasy rails and long ascends during poor weather conditions like precipitation or icing, which lead to a significant drop in track adhesion coefficient.

Thus, to prevent stalling, it is necessary to identify excessive skidding and take actions to increase track adhesion or reduce traction efforts of the electric motors (TEM) before the locomotive stalls. Therefore, traction rolling stock is equipped with various antiskid and extra-load devices, as well as the pneumatic sand-feeding system.

Class III traction drives are used more and more often to reduce the impact of the locomotives on the tracks, use the adhesion weight more efficiently, and reduce the probability of excessive skidding and stalling. These drives transfer the torque from TEMs to the drive wheels via quill drives. Traction and braking efforts are transferred from bogie frames to the cab through reclined rods that replaced pneumatic loading devices. Besides, spring suspensions are complemented with efficient shock absorbers and flexicoil bearings.

Despite the successful development of TEM control systems, class III drives cannot eliminate the risk of driving axle skidding. Today, feeding quartz sand to the wheels of the locomotive through its sand feeding system is one of the most efficient and popular methods of increasing the wheel-and-rail adhesion. It is assumed that the average efficiency of feeding sand to wheels is between 10 and 30%
The changes in the design of modern locomotives require upgrading the sand feeding systems. We believe that using a continuous sand feeding system is one of the most promising solutions in this case. Its implementation is described in this work [2].

2. Methods

This work aims to develop mathematical models that can describe the dynamic processes in the locomotive traction drive under various operating conditions considering the operation of a sand feeding system. The models must describe the train motion, the dynamics of the mechanical section in the traction drive, and the key parameters of the driving wheel and rail contact. The sand feeding system must be equipped with a control system that reacts to the changes in the state of the traction drive and ambiance model.

We will use the simplified train motion equation (1) as a basis to evaluate the operation of the sand feeding system and locomotive motion pattern. For the sake of convenient numerical integration, we will write this equation as a system of first-order ordinary differential equations in the normal Cauchy form. This system allows for the accounting of the traction performance of the locomotive and the resisting force acting on the locomotive as a mass point. The contact track adhesion force is accounted for indirectly via the traction performance, which helps calculate the traveling speed and the distance covered.

\[
\begin{align*}
q_1 &= q_2, \\
q_2 &= \frac{(F_k - W)}{m_p}.
\end{align*}
\]

where  
- \( F_k \) is the rail tractive effort (on the rim of the driving wheel) of the locomotive, N;  
- \( m_p \) is the number of cars in the train, pcs;  
- \( W \) is the motion resistance force, N;  
- \( W = (w_0' - i_c g)P + (w_0'' + i_c g)Q \); here, \( Q \) is the weight of the train (cars) in t; \( P \) is the charged locomotive mass with 2/3 of the sand stock in t; \( w_0' \) is the specific net resistance of the electric locomotive (drive movement), \( H/\tau \); \( w_0'' \) is the specific net resistance of the train (cars), N/g; \( g \) is the gravity factor, \( g = 9.81, \text{ m/s}^2 \); \( i_c \) is the effective grade, i.e. in curve effect, \( \theta/90^\circ \);  
- \( i_c = i + w_c \); here, \( i \) is the grade (ascend or descend), (+) is used for ascending and (−) for descending, \( \theta/90^\circ \); \( w_c \) is the secondary specific resistance of the rolling stock moving along the curve, N/g;

Let us review class III and class I traction drives.

To improve the sand feed, we will only need the diagram of the class III frame support drive of an electric freight locomotive shown in (Figure 1).

![Figure 1. Design diagram of a class III support axle drive](image)

The Figure uses the following legend: \( M_t \) is the torque on the TEM shaft, \( M_c \) is the track adhesion torque, \( J_r, J_{kp} \) are the inertia moments of the electric motor and the wheel pair, \( c_m, \beta_m \) are the equivalent torsional rigidity and the damping factor of the couplings and quill shaft.
The motion equations for the wheel pair approaching the stalling limits, according to Figure 1 and equations (1) will look as follows:

\[
\begin{aligned}
\dot{q}_1 &= q_2, \\
\dot{q}_2 &= \frac{(F_{kc} - W)}{m_p}, \\
\dot{q}_3 &= q_4, \\
\dot{q}_4 &= \frac{(-\beta_m (q_4 - q_6) - c_m (q_3 - q_5) + M_t)}{J_r}, \\
\dot{q}_5 &= q_6, \\
\dot{q}_6 &= \frac{(-\beta_m (q_6 - q_4) - c_m (q_5 - q_3) - M_c)}{J_{kp}}.
\end{aligned}
\] (2)

where \(q_1, q_2, q_3, q_4, q_5, q_6\) are the generalized coordinates: the distance traveled by the locomotive, the locomotive speed, the angular distance of the TEM shaft, the angular speed of the TEM shaft, the angular distance of the wheel pair, and the angular speed of the wheel pair.

The traction torque can be determined from the mentioned traction performance because system (2) describes the movement of the limiting wheel pair.

\[ M_t = \frac{\dot{F}_k}{R}. \]

Thus, the electric locomotive traction effort

\[ F_{kc} = M_c R. \]

Let us describe the track adhesion torque using [3]. Thus

\[ M_c = R P_o \psi_o k(\psi_{kp}) \] (3)

where \( R \) is the wheel radius, \( R = 0.625 \) m;
\( P_o \) is the axial load of the locomotive wheels on the rail in kN;
\( \psi_o \) is the non-dimensional adhesion coefficient for the locomotive starting from a standstill;
\( \psi_{kp} \) is the wheel sliding speed in rad/s;
\( k(\psi_{kp}) \) is the non-dimensional parameter showing the ratio of the immediate adhesion coefficient \( \psi \) to its maximum value when the locomotive starts from a standstill \( \psi_o \) depending on the wheel sliding speed.

The adhesion coefficient at starting from a standstill can be determined according to [4, 5]

\[ \psi_o = \frac{0.36(49 + 4.5v - 0.01v^2)}{50 + 6v} \]

where \( v \) is the locomotive speed in kmph

The non-dimensional parameter \( k \) can be expressed as a function

\[ k(\omega_{sl}) = \frac{\omega_{sl}}{a\omega_{sl}^2 + b\omega_{sl} + c} \]

(4)

where \( \omega_{sl} \) is the wheel pair sliding speed in rad/s;
\( a, b, c \) are non-dimensional coefficients.
Wheel pair sliding speed

\[ \omega_{sl} = \dot{\phi}_{sl} = \dot{\phi}_{kp} - \frac{\dot{x}_t}{R} \]

where \( \dot{x}_t \) is the locomotive traveling speed in m/s.

Coefficients \( a, b, c \) (3) can be calculated using the following conditions

\[ k(\omega_{sl}) = 1, \quad \frac{dk(\omega_{sl})}{d\omega_{sl}} = k'(\omega_{sl}) = 0 \text{ at } \omega_{sl} = \omega_{cr} \]

\[ k(\omega_{sl}) = 0,3 \text{ at } \omega_{sl} = 10. \]

Critical sliding speed values \( \omega_{cr} \) are picked from Table 1.

**Table 1.** The function of critical wheel sliding speed \( \omega_{cr} \) versus the locomotive traveling speed.

| \( V \), kmph | 0-5 | 10 | 20 | 40 | 60 | 100 | 120 |
|---------------|-----|----|----|----|----|-----|-----|
| \( \omega_{cr} \), с-1 | 0.04-0.1 | 0.1-0.2 | 0.2 | 0.25 | 0.35 | 0.6 | 0.7 |

The authors found an analytical solution for the coefficients in formula (3)

\[
\begin{align*}
a &= \frac{70}{3 (\omega_{cr}^2 - 20 \omega_{cr} + 100)} \\
b &= \frac{3 \omega_{cr}^2 - 200 \omega_{cr} + 300}{3 \omega_{cr}^2 - 60 \omega_{cr} + 300} \\
c &= \frac{70 \omega_{cr}^2}{3 \omega_{cr}^2 - 60 \omega_{cr} + 300}
\end{align*}
\]

Thus, in our further calculations, we assume that the track adhesion torque depends both on the wheel pair sliding speed and the locomotive traveling speed.

For class 1 drives, we will use the computational pattern shown in Figure 2.

**Figure 2.** The computational pattern of a class 1 support axle traction drive

According to Figure 2, the computational pattern uses the following legend. \( c_1 \) is the vertical track stiffness; \( \beta_1 \) is the track damping factor; \( c_2 \) is the stiffness of the spring suspension; \( \beta_2 \) is the spring suspension damping factor; \( c_3 \) is the stiffness of the TEM suspension on the bogie frame; \( \beta_3 \) – is the damping factor of the TEM suspension on the bogie frame; \( c_4 \) is the rigidity of longitudinal bracing of the wheel pair and the bogie frame; \( \beta_4 \) is the damping coefficient for the bracing of the wheel pair and...
the bogie frame; \( o \) is the center of the inertial coordinate system; \( c \) is the gravitational center of the TEM on the wheel pair axle; \( L_1 \) is the distance between the wheel pair axle and the TEM gravity center and its armature; \( L_2 \) is the central of the driving gear; \( L_3 \) is the longitudinal TEM suspension base on the bogie frame; \( \alpha \) is the horizontal tilt angle of the driving gear central; \( B_1, B_2 \) and \( B_3 \) is the wheel pair, TEM and armature case; \( M \) is the positive direction of the torques.

We use the angular displacement values of the wheel pair, TEM and motor armature cases, and the distance traveled by train as generalized coordinates. The angular displacement of the armature depends on the angular displacement of the wheel pair and the TEM case.

\[
\varphi_3 = -u \varphi_1 + (u + 1) \varphi_2
\]

To build a mathematical model, we will use 2nd order Lagrange equations.

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} = Q_i
\]

where \( T \) is the kinetic energy;

\( q_i \) are generalized movements;

\( \dot{q}_i \) are generalized speeds;

\( Q_i \) are generalized forces.

Expressing the kinetic energy of the system

\[
\frac{f_1 \varphi_1^2}{2} + \frac{f_2 \varphi_2^2}{2} + \frac{f_3 (-u \dot{\varphi}_1 + (u + 1) \varphi_2)^2}{2} + \frac{m_1 \dot{x}^2 + \dot{y}^2}{2} + \frac{m_p \dot{x}_p^2}{2} + \\
\frac{m_2 (l_2^2 \varphi_2^2 + l_1 (-\sin(\alpha) \dot{x} + \cos(\alpha) \dot{y}) \varphi_2 + l_1 \sin(\alpha) \dot{\varphi}_2 \dot{x} + l_1 \cos(\alpha) \dot{\varphi}_2 \dot{y} + \dot{x}^2 + \dot{y}^2)}{2}
\]

The motion equations look as follows:

\[
\begin{align*}
W - c_4 (x - x_p) - \beta_4 (\dot{x} - \dot{x}_p) + m_p \ddot{x}_p &= 0 \\
c_4 (x - x_p) - f_1 + \beta_4 (\dot{x} - \dot{x}_p) + m_1 \ddot{x} - m_2 (l_1 \sin(\alpha) \dot{\varphi}_2 - \dot{x}) &= 0 \\
c_2 \dot{y} - c_1 (\eta - \gamma) + c_3 (l_3 \sin(\varphi_2) + \gamma) - \beta_1 (\dot{\eta} - \dot{\gamma}) + \beta_2 \dot{y} + \beta_3 (l_3 \cos(\varphi_2) \dot{\varphi}_2 + \dot{y}) + m_4 \ddot{y} + m_2 (l_1 \cos(\alpha) \ddot{\varphi}_2 + \dot{y}) &= 0 \\
j_1 \ddot{\theta}_1 + j_3 u (u \ddot{\varphi}_1 - (u + 1) \dot{\varphi}_2) &= M_1 - M_3 u \\
-c_3 l_3 (l_3 \sin(\varphi_2) + \gamma) \cos(\varphi_2) + \beta_2 l_3 (l_3 \cos(\varphi_2) \dot{\varphi}_2 + \dot{\gamma}) \cos(\varphi_2) + j_1 \ddot{\theta}_1 - j_3 (u + 1) (u \ddot{\varphi}_1 - (u + 1) \dot{\varphi}_2) + l_1 m_2 (l_1 \ddot{\varphi}_2 - \sin(\alpha) \ddot{x} + \cos(\alpha) \ddot{y}) &= M_2 + M_3 (u + 1)
\end{align*}
\]

Equation system (5) \( M_1, M_2 \) and \( M_3 \) features torques applied to the wheel pair, TEM case, and motor armature. The operator before torques is selected depending on the direction of the train.

Solutions (2) and (5) in many practical situations lead to significant sliding speeds, i.e. To wheel skidding and stalling. This happens because real electric locomotives use control systems that prevent such events, and equations similar to (2) are mostly considered by researchers in quasi-stationary modes. To bypass these restrictions, we must consider the TEM control system.

In this work, we suggest using fuzzy logics instead of modeling a huge and complex electric locomotive control system. This approach helps reduce the time required to develop a model, and we will receive a modeled locomotive movement compliant with the field tests.

Let us express the TEM torque as follows:
$M_t = M_{ft} = w \frac{F_k}{R}$, \hspace{1cm} (6)

where $w$ is the coefficient depending on the decision-making systems based on the fuzzy logic and sliding values $v_{sl} = \omega_s R$. Then, $w = \text{fuzzySystem}(v_{sl})$.

To exclude the human factor in constructing membership functions at the inputs and outputs and in developing fuzzy rules, we performed global optimization using a genetic algorithm. Let us take the maximum distance traveled by the locomotive over time $t_f$ as the target function.

$$J = \max S.$$ \hspace{1cm} (7)

Let us show how to include the sand feeding system into models (2) and (5).

Let us introduce the following notions:

Function $M_s = \{(u', m_s(u')): u' \in X_u\}$ features sand stock value domain $M_s$, and dabbling definition domain $X_u$.

Function $S_e = \{(x, s_e(x)): x \in M_s\}$ sets the correlation between the amount of sand $M_s$ and the increase of friction factor $S_e$. Based on, we assume that $S_e = \{x \in R | 15 \leq y \leq 30\}$ is expressed as a percentage. Let us rewrite the control system shown in [6] as follows

$$M_s = \{(x, y, z, \text{fuzzySystem}(x, y, z)): x \in X_u, y \in v_{sl}, z \in q_2\} \hspace{1cm} (8)$$

Track adhesion torque under control of (10)

$$M_c = M_{fc} = \mu_n M_c = \mu_n R P \psi_k (\phi_k p) S_e'$$ \hspace{1cm} (9)

where $S_e'$ is determined as $0,01 S_e + 1$.

Let us rewrite (8) in a way that is convenient for optimization and leave only $v_{sl}$ as the input parameter. Thus

$$S_e' = \{(x, \text{fuzzySystem}(x, y, z)): x \in v_{sl}\}$$

3. Results

Let us present the results of motion modeling for a class III drive locomotive. We will perform calculations for different grade values shown in Figure. 3, depending on the distance. A typical traction performance of an electric locomotive is shown in Figure. 4. We should point out that in this case, the specific curve is not very important because the control system (5) allows for discrepancy compensation.

**Figure 3.** Effective grade values.

**Figure 4.** Locomotive traction performance.
If we vary the ambiance parameters as shown in [4], the moisture content will change along the locomotive route as shown in Figure 5.

**Figure 5.** Changes in moisture content (a) and friction factor (b) along the train route.

Figure 6a shows the changes in track adhesion torque $M_c$ as compared to traction effort torque $M_t$, which is determined using the traction performance in this chart. The ‘drops’ of the track adhesion torque can be explained by external impacts. The figure shows that the control system compensated for the reduced track adhesion by reducing the traction effort torque and sand feeding, which is reflected by the rapid recovery of the traction effort torque values $M_t$.

Figure 6b shows the operation of the antiskidding systems of the locomotive [6]. For instance, the system counteracted the external factors throughout the entire travel distance by reducing the TEM torque and feeding sand when the sliding speed exceeded the limit value. The sand feeding system worked until the lower limit of 0.2 m/s was reached.

The charts shown confirm the operability of the developed mathematical model and the correctness of the results obtained with its help.

The modeling results for the operating sand feeding system, such as the distance traveled and the train speed correspond with the solution (1), which signifies that the sand feeding system fully compensated the track adhesion changes occurring due to the moistening of the rails.

**Figure 6.** The track adhesion torque $M_c$ and traction effort torque $M_t$ change chart for an active sand feeding system (a) and the sliding speed of the locomotive driving wheels (b) for the wheel pair approaching the stalling limits.
4. Conclusion

We obtained the following results:

1. The train movement equation (1) can be used as a basis to assess the efficiency of the sand feeding system and determine the best movement parameters possible.

2. The maximum distance traveled over a specified time was used as the quality criterion for the sand feeding system and the main function in solving the optimization problem through a fuzzy logic system. The solutions obtained prevent skidding both with or without sand feeding if the ambient conditions are favorable, which corresponds to the field test results.

3. We constructed a mathematical model that takes into account the train motion resistance forces and the dynamic processes in the traction drive. The model reflects the key parameters of the locomotive wheel and rail adhesion, including the relation between track adhesion and sliding. We simplified the methods for calculating $k(\omega_{sl})$ coefficients through obtaining analytical dependencies.

4. To create a control system for continuous dosed sand feed, we used a fuzzy logic approach that mitigates the human factor in the developer's control system synthesis. The suggested model and its notation allow using genetic optimization algorithms to find membership function values for input and output parameters, as well as synthesize a rule base.

5. References

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