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Dynamics of sliding contacts in mine slow – speed railway transportation

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*Paper presents and discussed results of investigation as well as simulation of a sliding contact dynamics when used in a slow – speed railway of a copper mine transportation***.**

Keywords: *sliding contacts, dynamics, mathematical model, Cu-Mo composition slow-speed railway transportation, copper mine.*

Introduction

Contact dynamics under operation is a key factor for all contact switches independently on their structure and applications. However, in mine slow-speed railway transportation due to particularly onerous both operational (DC load 250 V, 250 A) and environmental conditions (high humidity and temperature, salt etc.) it affects the sliding contact performance significantly because of variation of the contact force value under work. It in turn influences the contact dynamic resistance thus amount of energy dissipated within the contact area what at elevated temperature leads to increased contact material damage and decreased its service life [1—3].

In the paper, basing on the investigated results a simplified mathematical model of the sliding contacts used in the slow-speed mine railway transportation has been developed. Computations were performed for different selected operational parameters and different speed value of the locomotive. On the basis of the simulations verified by experimental results the conclusions on the influence of the sliding contact dynamics on the contact set performance, when used Cu—Mo composition as the contact material are formulated.

Estimation of the mechanical parameters of the sliding contact set

To develop a simplified mathematical model of the real sliding contact set one has to determine reduced mass, compliance and spring values of ideal lumped elements representing the slider and trolley wire. View of the pantograph structure (contact slipper) used in a copper mine — haulage locomotive (LdT-31) is presented in fig. 1 while its simplified sketch with measured mass ($m_1 – m_6$) in kg and length in m of important mechanical elements ($l_2 – l_4$) can be seen in fig. 2.

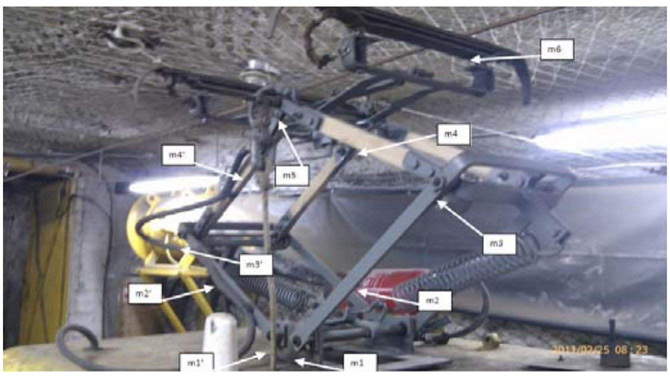

Fig. 1. View of the pantograph of a LdT-31 electric locomotive with indication of important elements (m1, m1' — clamping joints, m2, m2' — lower frames; m3, m3' — upper clamping pints; m4, m4' — upper frames; m5 — universal coupling; m6 — sliding contact member).

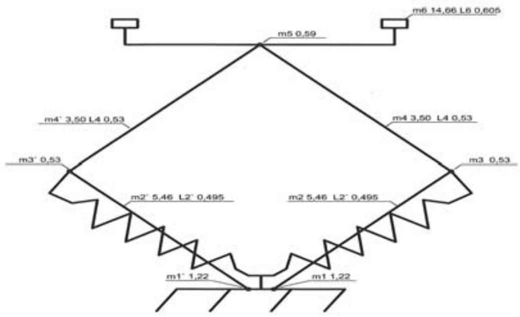

Fig. 2. Sketch of the pantograph with indication of particular, important elements as in fig. 1 (*m* — mass in kg, *L* — length in m).

For simplicity of calculations (with accuracy acceptable in practice) the sliding contact has been depicted by the simplest vibratory system having one degree of freedom. Since, the description is in the form of a differential used equation of motion thus, to perform the system identification we measurements of the step response (for different force value) to estimate equivalent reduced mass — *m*, spring constant — *k* and damping ratio *b* of both pantograph system and trolley wire. The step response was performed for as the trolley wire itself as well as for the pantograph and the wire system being in contact as in fig. 3

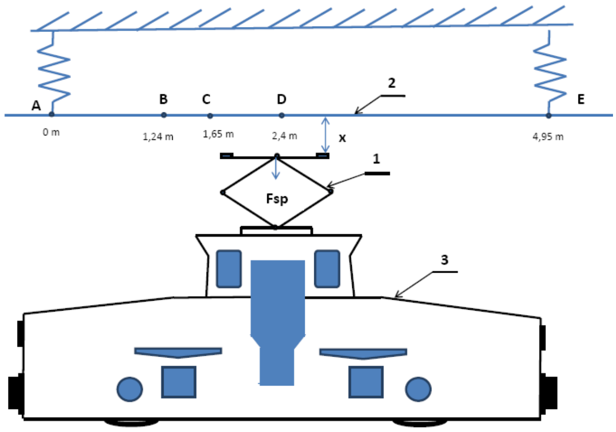

Fig. 3. Way of the system identification: 1 — pantograph (contact slipper); 2 — trolley wire; 3 — locomotive; F_{sp} — step force under test.

T a b l e 1. Relation between reversed force F_{sp} value, the contact slipper displacement *x* and spring constant *k* of the pantograph itself

F_{sp}, N	*x*, m	*k*, N/m
86	0,02	4300
94	0,03	3133
90	0,04	2250
102,5	0,05	2050

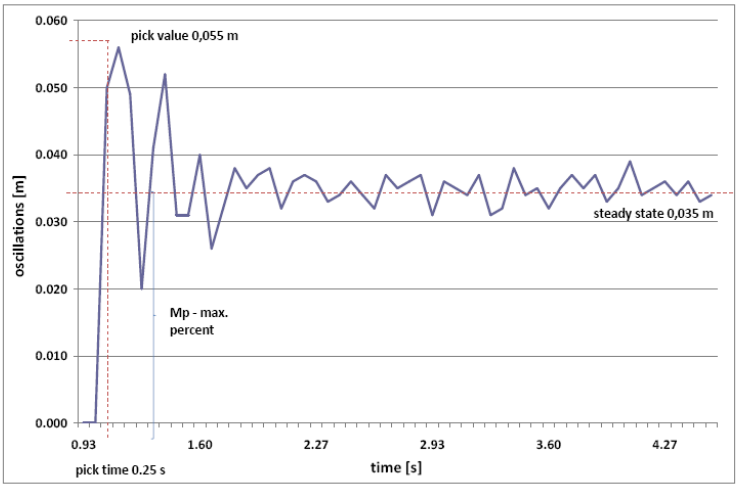

Fig. 4. Plot of measured step response of the pantograph-wire system at selected point D (see fig. 3).

Since the parameter values depend on the sliding contact location on the wire hanging therefore, the vibrations were measured for selected points (A…D) along the wire between its places of elastic fastening to the shaft ceiling (A – E) to calculate average values of mass, spring and damping constants. The spring value k of the pantograph was determined when remove it from the trolley wire by distance of 0,02—0,05 m under steady state mechanical force F_{sp} of magnitude as indicated in table 1.

Next, the force F_{sp} was removed and the response was recorded. Fig. 4 shows the response of a system to a step input of magnitude 102,5 N at D point (as in fig. 3).

From the graph, we see that the peak value is around $x \cong 0{,}055$ m so the maximum percent overshoot is $M_p = [(0{,}055 - 0{,}035)/0{,}035]\cdot 100 = 57\%$.

From the step-response specification for the linear second — order model, we may compute the damping ratio as follows [4]:

$$A = \ln\left(\frac{100}{M_p}\right) = \ln\left(\frac{100}{57}\right) = 0{,}562; \quad \xi = \frac{A}{\sqrt{\pi^2 + A^2}} = 0{,}176.$$

The peak occurs at $t_p \cong 0{,}25$ s thus, from [4]

$$t_p = 0{,}25 = \frac{\pi}{\omega_n \sqrt{1-\xi^2}} = \frac{3{,}15}{\omega_n}.$$

Thus $\omega_n^2 \cong 158$ and

$$m = \frac{k}{\omega_n^2} = \frac{2050}{158} \cong 13 \text{ kg}.$$

From the expression for the damping ratio [4]

$$\xi = \frac{b}{2\sqrt{m \cdot k}} = \frac{b}{2\sqrt{13 \cdot 2050}} = 0{,}176.$$

Thus $b = 57{,}5$ Ns/m and the model (at D point) is

$$13\ddot{x} + 57.5\dot{x} + 2050x = f(t) \tag{1}$$

In similar way from the plot of measured step response at B point the model is:

$$17.4\ddot{x} + 30.6\dot{x} + 2050x = f(t) \tag{2}$$

For the trolley wire (D_{jp} 100 type of 890 kg/km) the spring constant measured at different location depends also on the force F_{sp} applied and value of the wire deflection (x). Its average values can be compared from table 2.

T a b l e 2. Average value of the trolley wire spring constant

Point	k, N/m
A	4037
B	3108
C	2578
D	2559

From the plot of measured step response of the wire at D point presented in fig. 5 the model is:

$$5.45\ddot{x} + 61.65\dot{x} + 2559x = f(t) \tag{3}$$

To compare it, for example at the C point it is as follows:

$$3.57\ddot{x} + 59.48\dot{x} + 2578x = f(t) \tag{4}$$

On the basis of the measurements a simplified model of the sliding contacts used in slow-speed mine railway transportation was able to be developed for further simulation of dynamics.

Simplified mathematical model of the sliding contact set

Sketch of the simplified mathematical model for simulation of the contact force variation under running of the mine-haulage locomotive is shown in fig. 6.

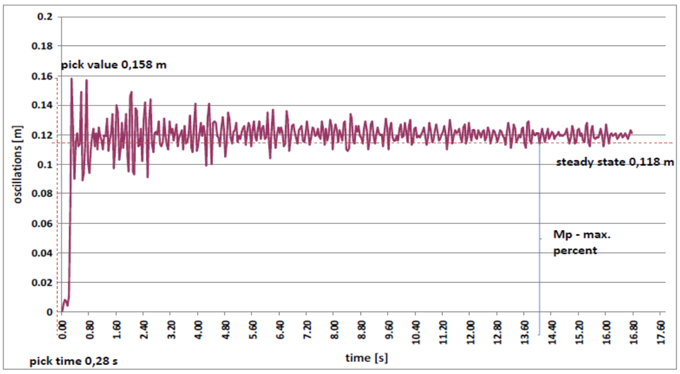

Fig. 5. Plot of measured step response of the wire itself at selected point D (see fig. 3).

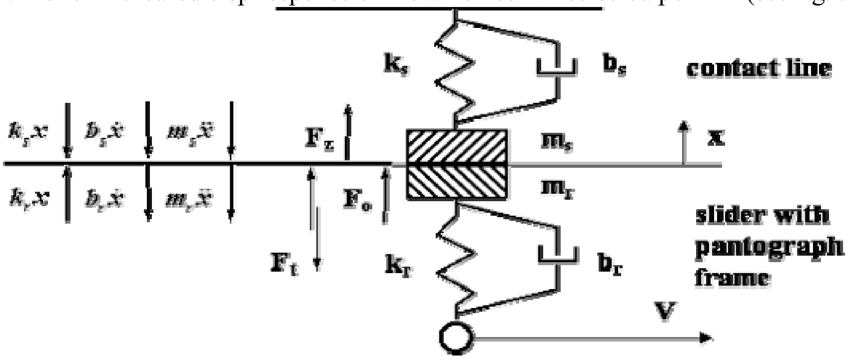

Fig. 6. Simplified model of the contact set for simulation.

This vibratory system can be described in form of a differential equation of motion as follows:

$$(m_r + m_s)\ddot{x} + (b_r + b_s)\dot{x} + k_s x = k_r x + F_o + F_z + sign(\dot{x})F_t \tag{5}$$

where x — displacement of the slider together with pantograph; F_o — force of the pantograph pressure for x = 0; F_z — disturbance force (expressed in F_o percentages); F_t — force of internal friction of pantograph coupling; k_r, k_s — spring constant of pantograph frame and contact line respectively; b_r, b_s — damping coefficient of pantograph and contact line sequent; V — tram movement.

Thus contact force F_c resulted from interaction of vibrated mass of the slider and this of respective segment of the trolley wire can be estimated from equations as follow:

$$F_c = k_r x + F_o - m_r \ddot{x} \tag{6}$$

Calculation results and discussion

Basing on values of mechanical parameters derived under the test the respective simulations were able to be performed using MATLAB. The most important for the contact performance is its maximum displacement under operation that is in a case of irregularity of the rails foundation and at maximum overhang of the contact line. Therefore in the paper are presented selected results of the displacement (x) and contact force (F_c) as a function of time for the case when the slider is located in the middle of the contact line segment (between spring mounting — see fig. 3). In a case of disturbance force ($F_z =$ = $0{,}2F_o$) lasting about 1s when the slider displacement (under steady state) x = 0,025 m the contact movement and its force variation in transient can be compared from fig. 7 and 8. One can see that the contact force value is still sufficient to ensure good conditions of operation of the sliding contact under load what was confirmed by the test [3]. Loss of the electrical contact however, can appear for considerable variation of the pantograph force pressure F_o with time when its initial value is equal to 0.

For the force F_o sudden increase to 150 N at $t_1 = 1$ s and following drop to zero (at $t_2 = 2$ s) the sliding contact operation in transient is very unstable what is seen from fig. 9. Similar situation is found for linear increase of F_o from 0 to 150 N (within 1 second) and next its decay to zero — see fig. 10. As a result the contact bouncing is found with respective arcing interruption of the load, what is not good for the contact reliability. Luckily, such the situation occurs only at turnouts and is rather seldom.

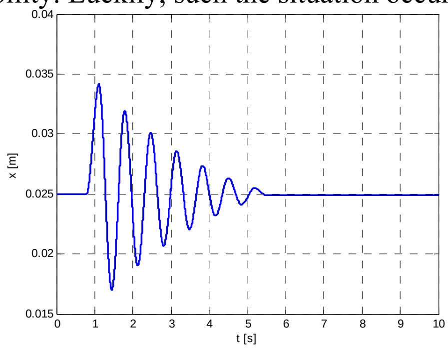

Fig. 7. Sliding contact vibration (x) with time under step disturbance force ($F_z = 0{,}2F_o$) at time $t = 1$ s.

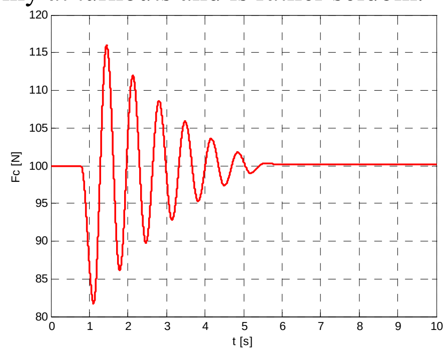

Fig. 8. Contact force F_c variation with time under influence of the step disturbance ($F_z = 0{,}2F_o$) at time $t = 1$ s.

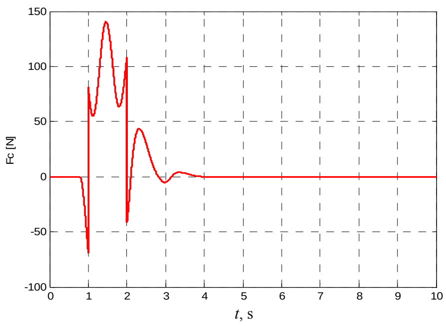

Fig. 9. Contact force F_c variation in time at sudden increase (at $t_1 = 1$ s) of the pantograph pressure to $F_o = 150$ N and following its drop (at $t_2 = 2$ s) to zero.

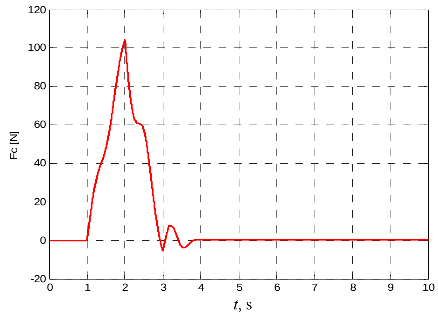

Fig. 10. Contact force F_c variation with time at linear increase of F_o from 0 to 150 N (between 1 and 2 s) and following its linear drop to zero (between 2 and 3 s).

Conclusions

Contact dynamics under operation that affect significantly contact force value is particularly important in mine slow-speed railway transportation due to onerous conditions of DC loading and environment (high humidity, temperature, salty air etc).

The contact resistance is thus increased at the decreased force value what at elevated temperature increases power loss within the contact area and leads to accelerated damage of the contact material. Particularly high damage is found for the sliders made of graphite commonly used in copper mine railway transportation.

We have found that situation is tremendously improved when replace graphite by Cu—Mo composition. However, the contact dynamics has to be carefully considered to avoid maloperations. Therefore, to develop the simplified mathematical model of the sliding contact the system identification basing on the measurements of the step response was performed. Having known reduced masses, spring constants and damping ratios we were able to specify a differential equation of motion and simulate variation of the contact force value for different situations. In general contact operation was found to be enough stable under work what was confirmed by the respective testing in real conditions of the copper-mine. However, the contact bouncing with related arcing is also possible in a case of rapid variation of the pantograph pressure particularly around its zero value. Luckily, such the situation takes place mostly at turnouts only and is rather seldom under operation.

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