Theoretical and experimental research on the phenomenon of stick-slip at traction railway vehicles

Ioan SEBESAN¹, Ion MANEA², Marius Adrian SPIROIU³, Sorin ARSENE⁴
¹,²,³Polytechnic University of Bucharest, Transport Faculty, Department of Railway Rolling Stock, Splaiul Independentei no. 313, Sector 6, Bucharest, Romania
²SC Softronic SRL, R&D Department, Craiova, No.40, Dolj, Romania,
ioan_sebesan@yahoo.com¹, ion.manea@softronic.ro², marius.spiroiu@yahoo.com³, sorin.arsene@upb.ro⁴.

Abstract: The stick-slip phenomenon may occur when the limit adhesion force is exceeded at one of the motor axles of the vehicle. In the present paper is analysed the physical phenomenon stick-slip, the conditions for its occurrence and the mechanical model recommended for the study of the phenomenon. Regarding the experimental research, it is presented the stand built in the laboratory of the Rolling Stock Department at Politehnica University of Bucharest.

Keywords: stick-slip phenomenon, rail vehicle, experimental results

1. General considerations

The motion of the drive axle may be accompanied by some intermittents or jerks, a phenomenon known in the speciality literature as stick-slip. As a consequence of the stick - slip, there are important dynamic overloads both in the axle and in its drive system, as well as variations in traction forces at the periphery of the wheels, which cause disturbance of the ride and thus reduce the traction performances of the vehicle.

Issues related to the stick-slip phenomenon will be analyzed for the case of the axle drive system with traction electric motor, at which the motor moment is transmitted to the traction gear by means of a torsion elastic shaft.

The stick - slip vibrations, the primary cause of which lies in the form of the wheel – rail friction and traction force characteristics, occur at low slide speeds, generally at the start of the vehicle, when it is possible the axle slip due to exceeding by the traction force of the limit force given by adhesion.
The time variation of the sliding speed of the wheel when the stick – slip occurs, experimentally determined by Schröter and Schönenberger [1], can be seen in fig.1.

Generally, vibrations that occur under the influence of dry friction on the wheel - rail contact are strongly depending on the sliding speed. Thus, at low slip speeds (Fig.2 a), the motion has an adherent phase (stick) and a sliding phase (slip), i.e. an intermittent sliding occurs when the friction force varies between a maximum level $T_{\text{max}}$ limited by adhesion and a minimum level $T_{\text{min}}$ corresponding to the friction coefficient at the maximum slip speed. At high slip speeds (Fig.2, b) autovibrations are produced, the amplitude of which is much lower than in the case of stick-slip.

The occurrence and development of the stick - slip is dependent on the variation law of the wheel - rail friction coefficient versus the slip speed.

In the case of axle sliding there is intense mechanical action between the particles of the wheel-rail contact surfaces, with a significant heat energy generation. The important modifications of the contact surfaces make the friction coefficient vary with the slide speed.

2. Factors that influence the stick-slip phenomenon

As is was highlighted before, the occurrence and time development of stick-slip depend on the variation of wheel-rail friction coefficient as a function of sliding speed.
The friction coefficient $\tau$ depends on the rail-wheel creep $v$, which is given by the ratio between the slip velocity $w$ the wheelset forward speed (the vehicle speed, practically) $v$, as demonstrated by F. Carter. In Levi's law, the characteristic of the coefficient of friction has an ascending branch up to the creep value $v_p$, corresponding to the maximum coefficient of friction (adhesion coefficient). As shown by Frederick F. [2], this characteristic has a descending branch for $v>v_p$ (see Fig. 1).

The stick-slip oscillations occur when the drive force $F$ and the friction force $T=\tau Q$, ($Q$ being the wheel load), are decreasing characteristics function of slip velocity $w$, for a given value of speed $v$- see Fig. 2.
The tangent in I intersect vertical $d\phi/dt = v/r$ in point R. Ordinate $m_g$ of this point defines the minimum value of wheelset torque. Straight line RM defines the possible limit (with maximum slope) of reduced torque characteristic.

Observations:

- The point R resulted as intersection of the tangent in inflection point I with the vertical in $d\phi/dt = v/r$. Any line starting from a point with the ordinate less than $m_g$ will intersect the decreasing branch characteristic of friction coefficient corresponding to the pure sliding in one or two points. If an intersection point is in the portion MI of the characteristic, then appears and the second point with ordinate less than $m_i$. Any line taken from a point with ordinate higher than $m_g$ intersect the characteristic in a single point.
- The line MR is characteristic limit of the torque reduced to the wheel (minimum slope)

### 3. Mechanical model for the study of stick-slip phenomenon

In Fig. 6 is shown an equivalent model of the driving system of motor wheelset. The occurrence of the stick-slip phenomenon can be explained as follows: in the slip velocity range $(0, w_p)$, the torque of the traction motor causes torsion of its elastic shaft and of the wheelset axle. Due to the fact that at the slip velocity $w_p$ the traction force $F_p > T_a$, $T_a$ being the adhesion force, the wheels start to slip with the acceleration of the drive system. At the same time, there is a tension release of the elastic elements from drive system and a reduction of the forces acting on the wheel circumference up to the point I where $F = T$. Further, the motion slows down, the adhesion is restored, and in the same time the engine torque increases until it exceeds again the adhesion limit and the motion repeats itself.
The system includes: the engine shaft on which acts the drive moment $M_m$, a torque shaft of the motor with a stiffness $k_c$, the assembly consisting of two-wheel gear with the transmission ratio $u$, transmitting the motion from the engine shaft to the wheelset axle having a stiffness $k_1$ and the two wheels of the vehicle on which act the moments $M_{t1}$, $M_{t2}$ of friction forces $T_1$, $T_2$.

$I_r$ – is the moment of inertia of the engine shaft;
$I$ - is the moment of inertia of vehicle wheel;
$I' = I + u^2 I_r$ - is the moment of inertia of the wheel, including reduced moment of inertia of the two-gear assembly drive axle, axle stiffness portion of it and the axle of the vehicle considering the infinite value;

$u$ is the gear transmission ratio;

$\varphi_r$ - is the angular displacement of electric engine shaft;

$\varphi_1$, $\varphi_2$ - angular displacements of the vehicle wheels.

4. Experimental model for the study of stick-slip phenomenon

In the laboratory of the Rolling Stock Department at Politehnica University of Bucharest has been developed a functional model of a motor vehicle bogie on which can be to modelled and experimented the wheel-rail interaction phenomena that occur when a fully equipped bogie runs on the rail (fig. 7,8,9).
The experimental stand for dynamic performance determination consists of a bogie model fitted with an axle and two wheels driven by an electric motor by means of an elastic shaft. In the lower part of the wheels there are provided two rails operated in the vertical direction by means of a rectangular metal frame provided with a helical screw (Fig. 9) in order to tighten the rails on the wheels. Each frame arm is equipped with four tensiometric marks, the force transducer thus realized having the possibility of measuring the traction-compression force from the bar driving the rails.

The electric motor is of the asynchronous type and has the possibility of modifying the speed, depending on the traction force we want to achieve. Depending on the braking force, the speed of the electric motor will change, even reaching the wheel lock. A tachometric probe with an infrared emitter - receiver system is used to measure the instantaneous speed.

There were determined the accelerations in the vertical and horizontal - longitudinal directions at the left and right journals of the axle by means of piezoelectric accelerometers. The measuring transducer chain is connected to an acquisition system that performs simultaneous 12-channel acquisition.
5. Conclusion

The stick-slip phenomenon, which occurs generally at the start of traction vehicles, has a negative impact on both the mechanical resistance of the elements of the axle drive system and the traction performance of the vehicle.

The mechanical model proposed for studying the stick-slip phenomenon was validated by the experimental results obtained on the stand in the laboratory.

It is worth mentioning that experimental determinations have also been made on a locomotive in starting regime. The measurements were consistent with those obtained in the laboratory, thus confirming the correctness of the mechanical model.

Acknowledgements

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS–UEFISCDI, project number PN-III-P2-2.1-PTE-2016-0008, within PNCDI III.

References

1. Sebeșan I, Mitu A-M, Sireteanu T., On the stick-slip phenomena in traction railway vehicles, Proceedings of the Romanian Academy, series A, vol. 16, nr. 2, 2015
2. Frederich F., Beitrag zur Untersuchung der Kraftschluss beins pruchurgen an schrögrollenenden Schienenfahrryeugrödern, Disertation TH Braunshweig, 1969
3. Kalker, J. J., Same new results in rolling contact, Vehicle System Dynamics,18, 1989
4. A. HAC, Adaptive control of vehicle suspension, Vehicle System Dynamics, 16, pp. 57–74, 1987
5. D. Stăncioiu, T. Sireteanu, M. Giuclea, A.M. Mitu, Simulation of random road profiles with specified spectral density, Proceedings of the Annual Symposium of the Institute of Solid Mechanics, Bucharest, Romania, pp. 331-338, 2003
6. Tyan, F., Hong, Y.-F., Tu, S.-H., and Jent, W. S., Generation of random road profiles, Journal of Advanced Engineering, pp. 1373 - 1378, 2009
7. S. Turkay, H. Akcay, A study of random vibration characteristics of the quarter-car model, Journal of Sound and Vibration, 282, pp. 111-124, 2005.
8. G. Verros, S. Natsiavas, C. Papadimitriou, Design optimization of quarter-car models with passive and semi-active suspensions under random road excitation, Journal of Vibration and Control, 11, pp. 581-606, 2005.