18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012
pp. 1543–1553
Paper #181

MEASURING OF WHEEL–RAIL ADHESION CHARACTERISTICS AT A TEST STAND

P. Voltr*, M. Lata, O. Černý*****

Abstract: *The properties of the adhesion contact of wheel and rail, expressed by the adhesion characteristic (non-linear dependence of tangential force on creepage), are of great importance for rail vehicle dynamics and drive regulation systems. The paper deals with the results of measurements of adhesion characteristics on a tram wheel test stand which was equipped with a new measurement chain in 2011 and provided a great volume of data. The measured characteristics are described, special attention being paid to the transitions which show influence of changes of friction conditions during the sliding.*

Keywords: ***adhesion, adhesion characteristic, experimental measurement, wheel–rail contact, sliding***

1. Introduction

The wheel–rail contact is a key element of the mechanical system of a rail vehicle moving along the track. The wheel and the rail, being flexible bodies, are deformed by the action of the vehicle gravitational force and a contact area is formed. The ability of transmission of tangential forces through this area under normal loading is, in the field of vehicle dynamics, referred to as adhesion.

The transmission of tangential forces is, also due to the flexibility of the bodies, inseparably connected with creep: there is a difference between peripheral and translational velocities of a powered or braking wheel rolling over the rail, even if apparent sliding does not take place. A significant property of the contact is a dependence of the transmitted forces upon kinematics of the bodies in contact. The dependence is expressed by adhesion (or, creep) characteristics – see e.g. Čáp (1999), Polách (2005). This paper is focused on the characteristic that has the greatest importance in drive dynamics: the longitudinal adhesion characteristic – dependence of the longitudinal tangential force (T) between the wheel and the rail on the longitudinal creep velocity ($w = \omega r - v$) or dimensionless creepage ($s = w / v$).

Several theories with various degree of simplification are available for description of the adhesion characteristic. Even the most accurate ones cannot, however, do without parameters, the values of which cannot be calculated but have to be measured. Therefore, experiments play an important role in this field of research. They are performed on test stands of various arrangement and size or on actual vehicles. The following sections describe the course and results of experiments conducted at the tram wheel test stand of the Jan Perner Transport Faculty in Pardubice.

2. The experiments

2.1. The test stand

The test stand on which the experiments were performed (see *Fig. 1*) was built by VÚKV (Výzkumný ústav kolejových vozidel – Rail Vehicle Research Institute) and underwent an extensive reconstruction at the Jan Perner Transport Faculty. The test stand has a main frame bearing a tram vehicle wheel (⌀ 700 mm) and a rotating rail (⌀ 905 mm) rolling over each other. The wheel is powered by

* Ing. Petr Voltr: Dopravní fakulta Jana Pernera, Univerzita Pardubice, Studentská 95, 532 10 Pardubice; CZ, e-mail: petr.voltr@student.upce.cz

** doc. Ing. Michael Lata, PhD.: dtto, e-mail: michael.lata@upce.cz

*** Ing. Ondřej Černý, PhD.: dtto, e-mail: ondrej.cerny@upce.cz

a permanent-magnet synchronous motor (PMSM), and the rotating rail is connected with an asynchronous motor. The wheel is mounted in a swinging arm and may be pressed to the rail by air pressure in a bellow. The rotating rail is mounted on a swivel base plate which enables adjusting the wheel–rail attack angle.

The test stand serves not only for adhesion experiments but also for development of PMSM regulation systems. The regulation of both motors is provided by frequency converters and a control computer. Originally, the measured signals were obtained directly from the memory of the control system. In 2011, however, a separate measurement chain was introduced, which enabled recording of data with higher sample frequency and, in particular, without limitation of the length of the recorded signal. The measurement chain contains incremental rotation sensors (IRC) at both wheels and a strain gauge torque transducer for measuring the torque at the rotating rail shaft.

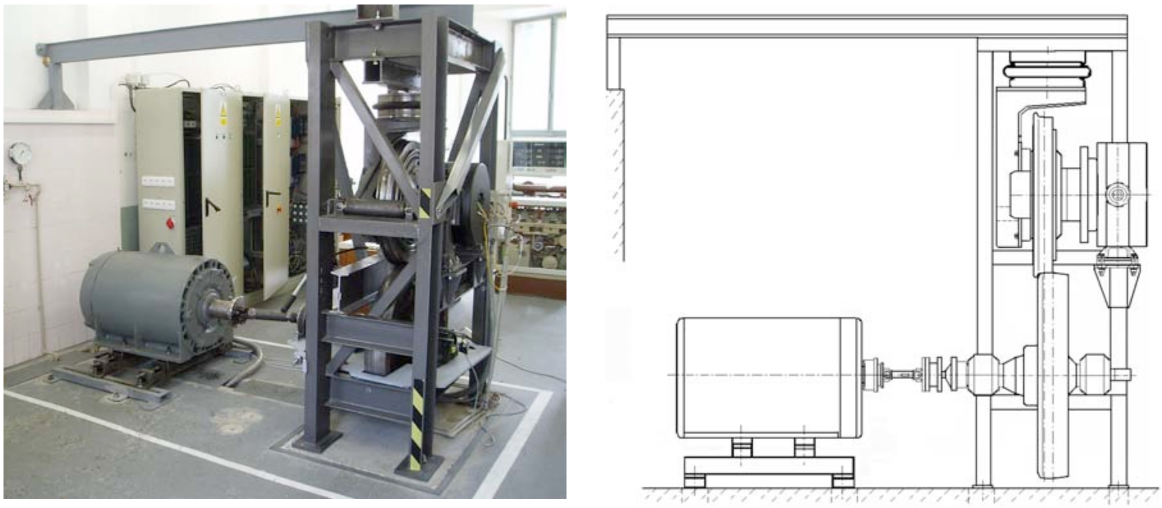

Fig. 1: The tram wheel test stand at which the experiments were performed

2.2. The course of the experiments

The aim of the experiments is to measure the dependence of the longitudinal tangential force acting between the wheels on the creepage or creep velocity not only during the effective slip (micro-slip), but also in the mode of full sliding. During the experiment, the torque of the tractive synchronous motor connected with the wheel is adjusted; it starts at zero and progressively increases until the adhesion capabilities of the contact are exhausted and the wheel starts sliding. After a short time, the torque is reduced until gross sliding terminates and the state of adhesion is restored. A direct transition into the mode of dynamic brake may also be made and sliding in opposite direction may be induced. The torque of the asynchronous motor which brakes the rail is automatically regulated so that the rail rotates with constant speed.

Magnitude of the force that may be transmitted depends significantly on the conditions of the surfaces in contact. In order to deteriorate the adhesion conditions in experiments (decrease the friction coefficient), lubricating oil was applied to the running surfaces. As the test stand is not equipped for continuous supply of oil, the surfaces are gradually cleaned by repeated sliding and the adhesion conditions get somewhat better during the experiments. Really good adhesion conditions are not, however, attained unless the surfaces are degreased by a solvent.

Experiments with non-zero attack angle were performed, too. In this situation, the wheel axis is not parallel to the rotating rail axis, which simulates the passage of a vehicle through a curve. Increased wear of the running surfaces occurs, since lateral slip is always present.

Each measurement record contains about ten measured adhesion characteristics for a constant rotational speed of the rail (corresponding to running speed of a vehicle of 10.3, 20.6 or 41.2 km/h). After each recording, the test stand was brought to a standstill and usually some of the conditions were changed; and a new output file was initialized on the PC's hard disk. In 2011, over 200 adhesion characteristics were measured during three days.

2.3. Data processing

The signals from the IRC sensors and the torque sensor are acquired by a personal computer equipped with an interface card. The data are recorded and saved as a text file by a program developed in the LabView environment. The files contain signals of time and values obtained from the three sensors with a sample rate of 200 Hz.

The values from the counters at both wheels are converted to angular position in radians and differentiated in order to obtain angular and peripheral velocities of the wheels. The difference of the peripheral velocities is the creep velocity w which, divided by the (almost constant) peripheral velocity v of the rotating rail yields the dimensionless creepage s.

The recorded voltage signal from the torque transducer is converted to the torque M_2 in Nm on the basis of a calibration measurement preceding the experiments. Further, the tangential force T and adhesion coefficient μ, defined as the ratio of the tangential and normal forces, is calculated. The signal is affected by both periodic and random parasitic components. The periodic component is brought about by mechanical imperfections of the test stand; it contains a fundamental frequency equal to the frequency of rotation of the rail and three or four harmonics. This parasitic effect is eliminated by a suitable filter – moving average with a window length precisely adjusted to the period of the rail rotation.

By plotting of the measured adhesion coefficient against the creepage, the adhesion characteristic is obtained (see *Fig. 4, 6, 7*). The measured characteristics have, as expected, a steep ascending effective branch, a peak at several percent creepage, and a slowly descending ineffective branch. In some cases, however, different shapes are observed, which is described and commented upon in the Section 4.

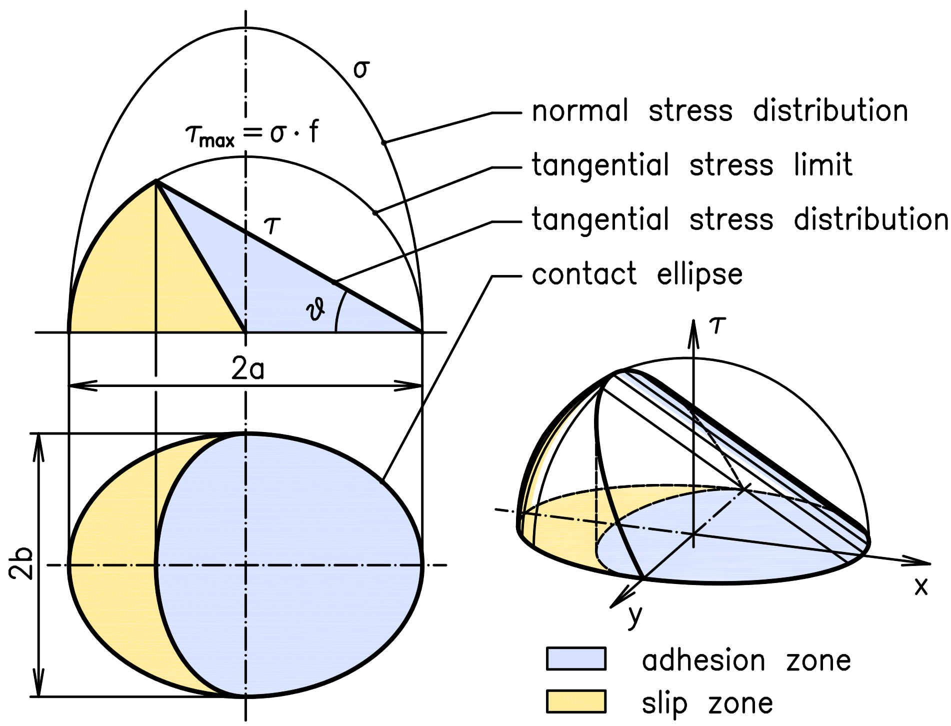

Fig. 2 Tangential stress distribution in the contact area in steady rolling with creep and the division of the area into zones of adhesion and slip according to Freibauer

3. Evaluation of the measured characteristics

3.1. The method used

Quantitative description of the measured characteristics may be made e.g. on the basis of the coordinates of the adhesion characteristic peak, or the tangent to the curve in the origin. In earlier times, researchers approximated the characteristics by polynomials, see Čejka (1970) or by piecewise linear functions. A more complex and useful description may be obtained if the Freibauer adhesion theory is employed – Freibauer (1983). The theory yields a function expressing the dependence of adhesion coefficient on creepage; the function is obtained as an analytical integration of the distribution of tangential stress in the contact area (see *Fig. 2*) in steady state rolling under certain simplifying assumptions on elastic properties of the material.

The measured adhesion characteristic is approximated by the function prescribed by the Freibauer theory; the quantitative description is then constituted by the set of parameters appearing in the function. Adjustment of the parameter values and assessment of accuracy of the approximation is performed by a human factor – no mathematical method is used, since the attempts to do so led to fair results in a limited number of cases only.

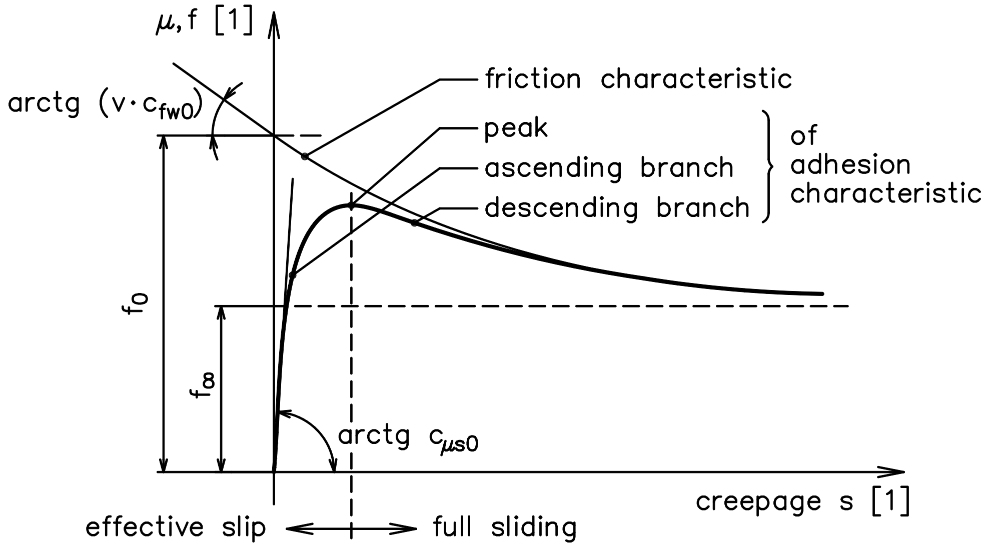

Fig. 3: A sketch of the theoretical friction and adhesion characteristics

3.2. The adhesion characteristic parameters

The Freibauer adhesion characteristic (see a sketch in *Fig. 3*) unites

- the dry friction force characteristic describing the dependence of friction coefficient f on the velocity of relative motion which is the creep velocity w,
- the saturation function describing the expansion of the slip zone in the contact area with increasing creepage s.

In our work, the extension of Freibauer theory developed by Polách (2005) is used. It includes an additional parameter which may be physically justified and which, according to the author, enables to achieve a closer agreement of theoretical and measured curves. Further explanation may be found in the cited article. In this paper, let us confine to the statement that the used formula is

$$\mu = \frac{2}{\pi} \cdot f \cdot \left(\arctan k_{\mathrm{S}} \varepsilon + \frac{k_{\mathrm{A}} \varepsilon}{1 + (k_{\mathrm{A}} \varepsilon)^2} \right) \tag{1}$$

where

$$k_{\mathrm{S}} \varepsilon = \frac{\pi}{2f} \cdot \frac{c_{\mu s0}}{1 + 1/\lambda} \cdot s \tag{2}$$

$$k_{\mathrm{A}} \varepsilon = \frac{\pi}{2f} \cdot \frac{c_{\mu s0}}{1 + \lambda} \cdot s \tag{3}$$

and the dry friction characteristic $f = \mathrm{f}(w)$ is exponential,

$$f = f_0 \cdot \left((1 - A) \cdot e^{-Bw} + A \right) \tag{4}$$

$$B = -\frac{f_0 \cdot c_{fw0}}{A} \tag{5}$$

Five parameters, the values of which are to be found, appear in the above formulae. These are:

1. $c_{\mu s0} > 0$ [1] – initial steepness of the ascending branch of the adhesion characteristic,
2. $c_{fw0} > 0$ [s/m] – negative initial steepness of the friction characteristic,
3. $f_0 > 0$ [1] – static friction coefficient,
4. $A \in \langle 0, 1 \rangle$ [1] – ratio of friction coefficient at $w \to \infty$ to the static friction coefficient,
5. $\lambda \in (0, 1\rangle$ [1] – ratio of the surface stiffness reduction coefficient in the area of slip k_S to that in the area of adhesion k_A (sharpness of the adhesion characteristic peak).

These formulae and parameters describe the same function as in Polách (2005), the difference consisting only in different expression of some parameters. The inclusion of the parameter λ in our work corresponds to the distinction of two reduction coefficients k_A and k_S in Polách's extension. The difference between these two formulations is as follows:

- Utilization of the parameters k_A and k_S requires the dimensions of the contact area and Kalker's creep coefficient c_{11} to be known. In return, values of two parameters presumably independent on contact geometry are obtained.
- Thanks to the expression of the same by the parameters $c_{\mu s0}$ and λ, the measured characteristic may be approximated even if the geometry of the contact area is not known. The parameter $c_{\mu s0}$ is, however, valid only for the present contact conditions.

The original Freibauer's function without this extension is equivalent to the extended function with $k_A = k_S$, thus $\lambda = k_S / k_A = 1$. The arithmetic mean $k = (k_A + k_S)/2$ equals to the reduction of Kalker's creep coefficient c_{11}. For the creep coefficients, see e.g. Kalker (1973).

An example of a measured characteristic approximated by a function with these parameters is shown in *Fig. 4*. The agreement of the measured and theoretical curves in their ascending branches and near their peaks is good and the inclusion of the parameter λ contributes to it (especially under degraded adhesion conditions). Our experiments thus confirm the suitability of Polách's extension to the Freibauer theory.

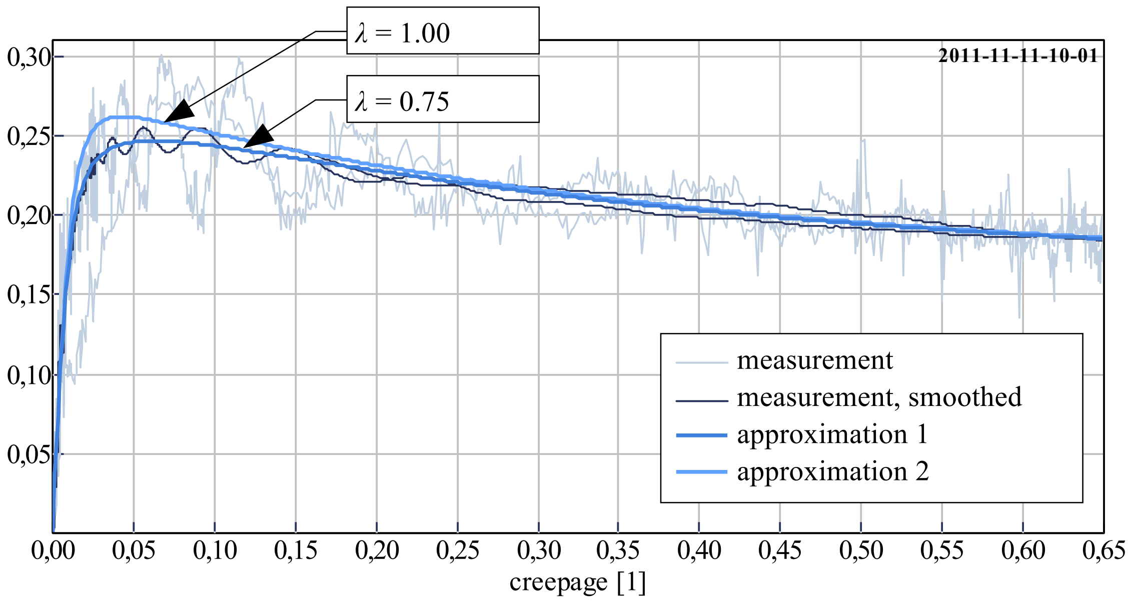

Fig. 4: Example of a measured and approximated adhesion characteristic showing the influence of the parameter λ. The function with λ = 0.75 is a better fit.

4. Changes of friction conditions during the measurement

4.1. Overview

Some measured characteristics may be well approximated by the theoretical function; a majority of them, however, has different shapes. The approximation may be used, but it is suitable only for a certain part of the characteristic. For instance, a characteristic may be approximated in the region of low slip (s < 0.3–0.5) and the agreement would be very good, but the same approximating function would not be appropriate for high-slip regions of the same measured curve. The measured characteristics include those with a peak at as far as s = 1–2 or those with multiple peaks.

In our opinion, these observations do not disprove the adhesion theory but document the variability of adhesion conditions during a single measurement. The plotting of a measured characteristic as a dependence of the adhesion coefficient on creepage should be regarded as a simplification, because it eliminates time. A correct graphical representation of measured data would have to use three coordinates: adhesion coefficient, creepage and time. In case the surface conditions change during the measurement, the plotted characteristic $\mu = \mathrm{f}(s)$ may not be expected to agree with a theoretical function with constant parameters. And it is obvious that the change of the conditions can occur – owing to the sliding, the running surfaces may be cleaned, worn and warmed, which changes the friction conditions.

Therefore, the measured adhesion characteristics are not approximated by a function with one set of parameters but by a zone defined by ranges in which the parameters vary, the formula itself remaining unchanged. Over a measured characteristic, two theoretical ones are plotted which delimit the zone; one of them is referred to as initial and the other as final.

4.2. Degraded adhesion conditions

In the case of experiments with degraded adhesion conditions where the running surfaces were contaminated with lubricating oil, the ascending branch of the measured characteristic is as expected; its peak is not very sharp and is located usually at s = 0.05 or higher. With the inception of gross sliding, the cleaning influence of sliding emerges: the contaminants are being forced out of the contact region or entirely removed from the wheels. The friction coefficient increases and the descending branch of the adhesion characteristic thus turns into a second increase. Further course depends on the operation of the traction motor (see *Fig. 5*):

1. if the sliding is terminated shortly, the surfaces do not get cleaned much and the adhesion characteristic returns through almost the same course when creepage is reduced;
2. if the increase in creepage continues above approx. 0.5, the return course then lies significantly higher and makes a closed loop;
3. if the creepage alternately increases and decreases several times, a waved curve or several loops appear in the plot;
4. if the wheel is allowed to slide on, at the creepage of s = 1–2 the increase in the tangential force ceases and a customary decreasing exponential dependence takes place; the return course more or less follows the same exponential function but usually lies somewhat lower.

The effect described in the last point (see *Fig. 6* left) shows that there is a stage at which a certain maximum possible cleaning occurs and a near-steady state is reached. It appears that varying one parameter of the theoretical adhesion characteristic is sufficient to express the observed change in friction conditions; it is the parameter f_0 – static friction coefficient. Whereas its initial value is usually 0.7–0.11, its final value – in case the mentioned near-steady state is reached – may be higher than 0.3.

In some cases of strong contamination by lubricating oil, adhesion characteristics have been recorded where there was no decrease in adhesion coefficient after full sliding began but an almost linear increase was observed (*Fig. 6* right). This increase was accompanied by strong torsional vibration and continued up to the creepage of s = 1–2 where it eventually turned into an expected dry friction exponential. Effects of hydrodynamic lubrication could have been taking place in the phase of linear increase. These effects, being dependent on the normal loading, presumably would not occur at a real vehicle whose vertical wheel load is considerably higher than at the test stand.

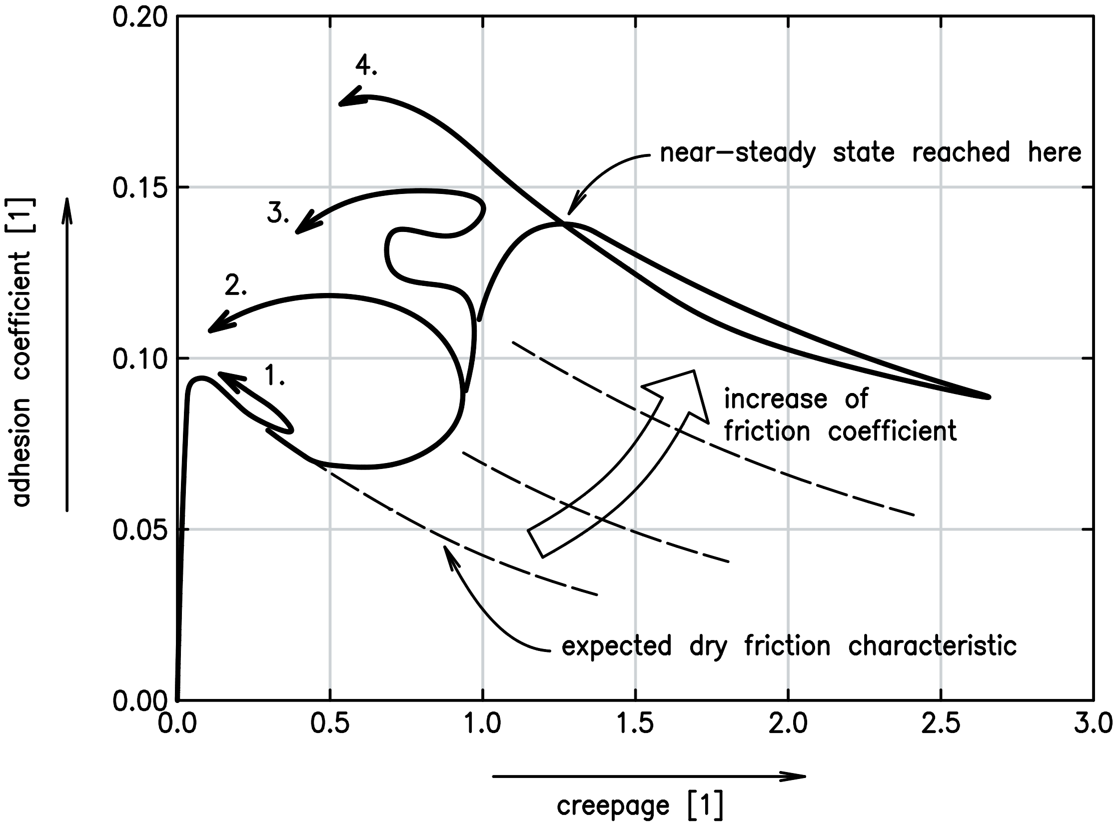

Fig. 5 A sketch of recorded adhesion characteristics showing influence of change of friction conditions during the sliding

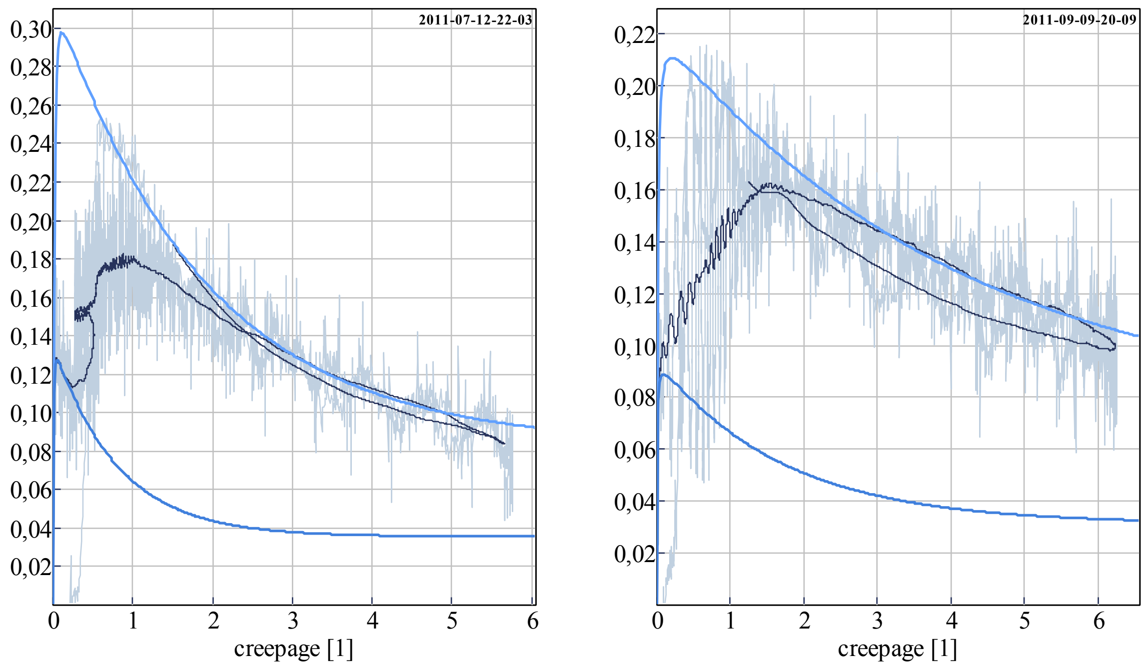

Fig. 6: Lubricated contact – adhesion characteristics: a curve with multiple peaks (left) and with a peak at s = 1.5 but no peak where it would be expected (right)

4.3. Good adhesion conditions

In general, it may be stated that the changes occurring under good adhesion conditions are less significant than the changes under bad conditions, which is comprehensible as in this case there is less contaminating material to remove from the contact. The steepness of the ascending branch is higher, as expected. The peak is sharper, and in case that the surfaces are degreased by a solvent, static friction coefficient f_0 of 0.40–0.45 is reached.

In the experiments where the traction motor torque was increased very slowly and rolling with effective slip was taking place for a long time (up to 50 s), the measured characteristics show a continual change at the ascending branch, too. The change may be modelled as an increase of the parameters $c_{\mu s0}$ and λ, and sometimes also f_0. This is illustrated in *Fig. 7* to the left, where the measured data are overlaid by the initial and final theoretical curves which differ in the values of $c_{\mu s0}$ and λ. If we tried to express the measured curve with one theoretical function with constant parameters, the agreement would never be close around the sharp peak.

Results of the measurements where creep velocity was not restrained from rising to high values show transitions at the descending branch. As opposed to the transitions under bad adhesion conditions, varying the parameter f_0 is not sufficient for expressing this transition. In the first place, the value of c_{fw0} has to be changed: transition to a less steep friction curve takes place. The theoretical curves plotted in *Fig. 7* to the right have slightly different values of f_0 (0.343 vs. 0.350) but more important is the difference of c_{fw0} (0.056 vs. 0.041). The two functions together can express a recorded one which has a higher steepness immediately after the peak ($s < 0.5$) than what corresponds to the rest (s = 2–6). The question is suggested whether there is any relation of the described shapes to the characteristics measured by Barwell (1957) and Čejka (1970), at which the peak is followed by a decrease so significant that it is denoted as a discontinuity.

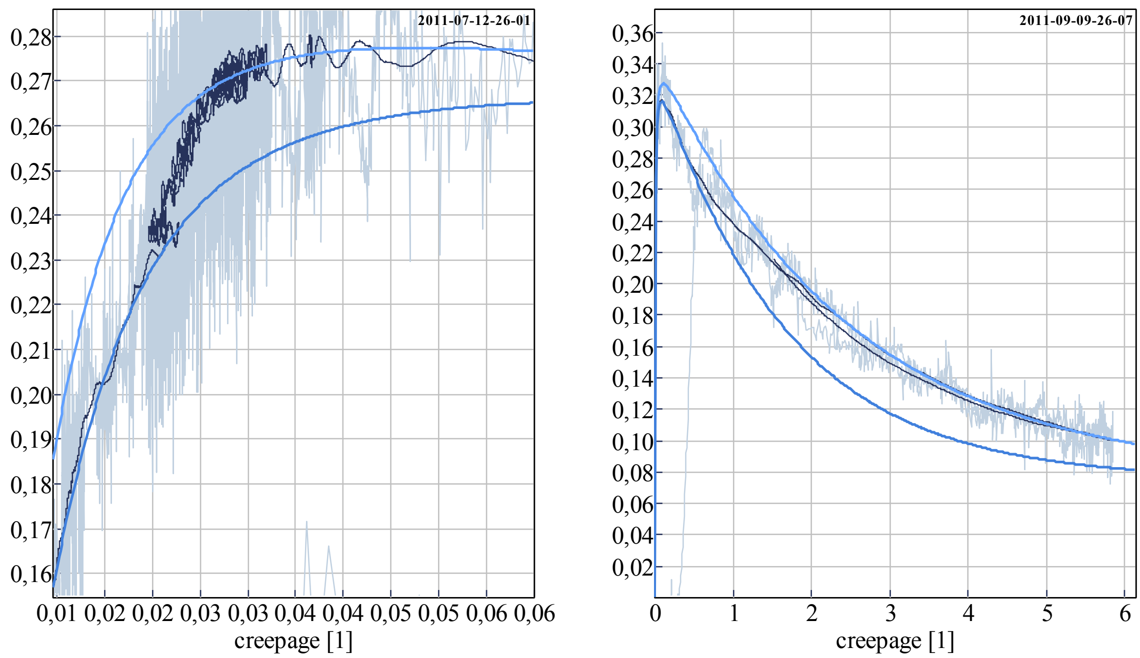

Fig. 7: Some measurement results under good adhesion conditions. Left: detail view of a peak exhibiting a transition at the ascending branch; right: a characteristic which clearly shows a transition at the descending branch.

5. Quantitative results

The static friction coefficient f_0 may serve for characterisation of the adhesion conditions. The lowest values – cca 0.07 – were naturally observed in the experiments before which the running surfaces were lubricated. During each occurrence of sliding that continued to high relative velocities, f_0 increased up to the values of 0.2–0.3. When adhesion was restored and afterwards sliding was induced anew, the friction coefficient did not start at 0.2–0.3, but at its lower values again: the phenomenon of cleaning was in effect during the sliding only.

As a consequence of repeated sliding, however, the initial friction coefficient value increased, too – up to approx. 0.28. A more substantial increase was reached by degreasing the surfaces: then, the friction coefficient would exceed 0.4.

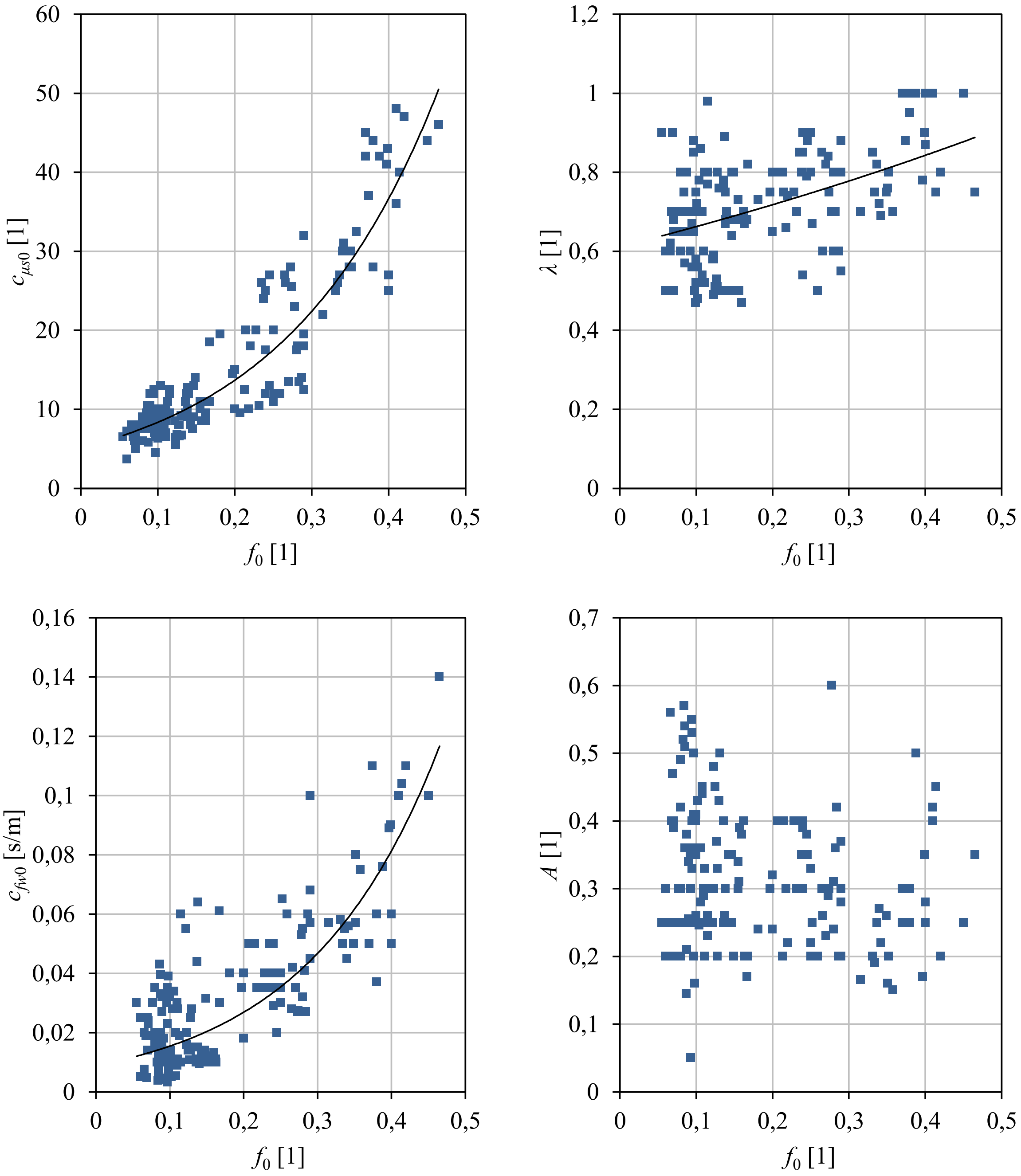

Fig. 8: Graphical representation of quantitative results. The static friction coefficient f_0 (horizontal axes) was chosen as a parameter describing the adhesion conditions; other four parameters are plotted against it. Each point corresponds to one measured characteristic. Measurements with non-zero angle of attack are not included.

It must be noted that the maximum reached adhesion coefficient μ_{max} is, due to the decreasing nature of friction characteristic, lower than the static friction coefficient f_0, as seen in Fig. 3.

The initial adhesion characteristic steepness $c_{\mu s0}$ also depends on adhesion conditions. This parameter of the adhesion model depends on the tangential stiffness of the surface layers of the bodies in contact which is lower if there is contaminant between them. Values of $c_{\mu s0}$ = 5–10 were observed with strongly lubricated surfaces; with increasing friction coefficient f_0 the stiffness clearly increases and reaches maximum values of about 50.

It should be emphasized that the initial steepness depends also on contact geometry and that in the case of a real vehicle running on real not rotating rails the value may differ – its values are higher, see Lata and Čáp (2010). The reduction coefficient k of Kalker's creep coefficient c_{11} has a similar meaning but is independent of the contact geometry. We cannot determine its value from the measurements but it may be supposed that the maximum steepness values which were reached under the best adhesion conditions correspond to an almost ideal state where Kalker's coefficient are not reduced ($k = 1$). Thus under the worst adhesion conditions in the experiments, the reduction would be $k = c_{\mu s0,\,\min}/c_{\mu s0,\,\max} = 5/50 = 0{,}1$.

The parameter λ has, according to our measurements, the value in a wide range of 0.45–0.95 under bad adhesion conditions; under good conditions, it is higher, up to 1.0 with degreased surfaces. That is the state which may be apparently regarded as almost ideal where the reduction coefficients k_S and k_A both approach to 1 whence their ratio λ approaches to the same number.

The initial steepness of the friction characteristic c_{fw0} is in a wide range of 0.002–0.04 s/m under bad adhesion conditions; with an increase of f_0 it increases, too, and under very good adhesion conditions it can exceed 0.1 s/m. Our measurements thus indicate that if the friction coefficient at zero relative speed w is higher, it decreases more rapidly with increasing speed.

The parameter A has a value about 0.2–0.55 under bad adhesion conditions. Under good conditions (dry surfaces) it tends to fall in a narrower range of 0.2–0.4. The parameter does not influence the shape of the adhesion characteristic until higher creep velocities; in the zone of $s < 0.5$, its value (within the mentioned range) is almost immaterial.

6. Conclusions

The paper deals with the course and results of adhesion measurements at a tram wheel test stand at the Jan Perner Transport Faculty in Pardubice. The test stands simulates rolling of a powered and braked wheel over a rail; the rail has a form of rotating rail, i.e. a wheel with a railhead profile. The processed measurement output gives dependences of the adhesion coefficient μ (ratio of the tangential and normal forces in the contact) on the creep velocity w or dimensionless creepage s. Evaluation of the output involves approximation of the measured adhesion characteristics by theoretical ones given by the Freibauer theory. Values of their parameters then quantitatively characterise the measured dependences and serve as input parameters in rail vehicle dynamics modelling – see Lata (2008), Voltr and Lata (2011).

Most of the measured characteristics may be approximated in this way in a certain range only. During the experiments, namely during gross sliding of the wheel, changes of surface conditions occur, wherefore the values of the parameters change even during the recording of a single adhesion characteristic. Thus each measured dependence is approximated not by a single theoretical function but by two of them (initial and final) between which there is a transition, which is left without description in this work. The approximation is often not unequivocal because it is difficult to decide in which region the measured course is near-steady and in which region it should be regarded as the transition. This fact affects the results with a subjective influence.

The conclusion is that the change of friction conditions during sliding should not be neglected if high sliding velocities are concerned. The influence is more significant under bad adhesion conditions – the contaminant is being removed during the sliding. The change may then be expressed by an increase of the parameter f_0 in the model. The consequence is that the descending branch of the adhesion characteristic falls more slowly or even may rise and form another peak. Its occurrence is not a property of the μ–s dependence but a consequence of change of friction conditions in time; the peak does not occur at the upper boundary of an effective slip mode but far higher in full sliding mode. Thus it appears not to be convenient to utilise the peak in slip regulation.

Even under good adhesion conditions, however, certain changes are encountered which may be modelled by increasing the parameters $c_{\mu s0}$ and λ, or decreasing the steepness c_{fw0}, respectively.

In the application of the results one should consider the following differences between the test stand and a real vehicle on a track:

- The substitution of a straight rail by a rotating one results in shortening the contact area in longitudinal direction and slight widening in lateral direction. The contact conditions are thus different.

- In our opinion, however, the difference of normal loading is more substantial – the vertical wheel force of a modern tram vehicle is 25–40 kN whereas at the test stand it is 4 kN.
- As another consequence of the use of rotating rail is that in rolling with sliding, the parts of the rail which have been cleaned by sliding come into the contact each time again; a real vehicle, on the contrary, moves continually over a new, contaminated sections of rails.

The observed changes of friction conditions during sliding imply suggestions for further work: it might be possible to express the changes mathematically e.g. in dependence on friction force work/power, see Blau (2009), Pugi et al. (2011). For validation of such a model it could be useful to perform experiments under the same conditions but with different speed of increasing and decreasing of creepage.

Acknowledgement

This work was supported by the University of Pardubice, project No.51030/20/SG520001.

References

Barwell, F. T. (1957) Několik výsledků o tření a opotřebení se zvláštním zřetelem na koeficient tření mezi kolem a kolejnicí. Transl. from German: Einige Ergebnisse über Reibung und Verschleiß unter besonderer Bezugnahme auf die Reibzahl zwischen Rad und Schiene. *Glasers Analen*, Hf. 2, 1957, pp. 231–261.

Blau, P. J. (2009) Embedding Wear Models into Friction Models. *Tribol Lett* 34, pp. 75–79.

Čáp, J. (1995) Teoretický rozbor tečných a interaktivních sil ve styku kolo–kolejnice. *Scientific Papers of the University of Pardubice*, Ser. B., 5 (1999), pp. 29–47.

Čejka, J. (1970) *Adhesní vlastnosti elektrických lokomotiv na střídavý proud.* Dissertation thesis, Vysoká škola dopravní v Žilině, Fakulta strojní a elektrotechnická.

Freibauer, L. (1983) Adheze kola vozidla na dráze, in: *7. vedecká konferencia Vysokej školy dopravy a spojov v Žiline – Zborník referátov*, VŠDS Žilina, pp. 214–219.

Kalker, J. J. (1973) Simplified theory of rolling contact. *Delft Progress Report*, Ser. C, 1 (1973), pp. 1–10.

Lata, M. (2008) The modern wheelset drive system and possibilities of modelling the torsion dynamics. *Transport*, 23(2), pp. 172–181.

Lata, M. & Čáp, J. (2010) The steepness of the rising branch of adhesive characteristics between wheel and rail. *Transport*, 25(1), pp. 17–21.

Polách, O. (2005) Creep forces in simulations of traction vehicles running on adhesion limit. *Wear* 258, pp. 998–1000.

Pugi, L. et al. (2011) Three-dimensional modelling of wheel–rail degraded adhesion conditions, in: *22nd International Symposium on Dynamics of Vehicles on Roads and Tracks – Proceedings* [CD]. Manchester Metropolitan University, Manchester.

Voltr, P. & Lata, M. (2011) Dynamical behaviour of a locomotive drive system at the adhesion limit – experiment and simulation, in: *22nd International Symposium on Dynamics of Vehicles on Roads and Tracks – Proceedings* [CD]. Manchester Metropolitan University, Manchester.