SCIENTIFIC PAPERS
OF THE UNIVERSITY OF PARDUBICE
Series B
The Jan Perner Transport Faculty
15 (2009)

NEW PRACTICAL RESULTS ABOUT ADHESION LIMITES OBTAINED FROM EXPERIMENTAL STAND TESTING

Michael LATA, Jaroslav ČÁP, Petr VOLTR

Research Centre of Rail Vehicles, Jan Perner Transport Faculty, University of Pardubice

1. Introduction

The autors are concerned to the theoretical and mainly practical research at the field of driving dynamics and adhesion problematics. Experimental research in the field of drive dynamics and adhesion issues is carried out at the Jan Perner Transport Faculty of the University of Pardubice. A special test stand (***Fig. 1***) with a rotating rail and a tram wheel was built.

The wheel is driven by a permanent magnet synchronous motor through a cardan shaft and a flexible coupling. An original electronic system is employed to regulate the synchronous motor. Such design is attractive for applications in low-floor vehicles with independently rotating wheels. The test stand was originally designed by VUKV a. s. (Rail Vehicles Research Institute) and underwent an extensive overhaul of both its mechanical and electrical parts. The main parts of the stand are: 1. supporting frame with a manipulation traverse, 2. air bellow for vertical loading, 3. driven wheel with a cardan shaft in its hollow, 4. revolution sensor, 5. permanent magnet synchronous motor, 6. rotating rail, 7. revolution sensor, 8. torque sensor, 9. braking asynchronous motor.

Rotational speeds of both wheels and torque transmitted on the rotating rail are measured at the test stand. Angular speeds of the tram wheel and the rotating rail are taken by precise revolution sensors. It should be noted that a research in the field of synchronous motor regulation is conducted by co-workers of the Department of Electrical and Electronic Engineering and Signaling in Transport at the test stand.

An original regulation software is used for moment and speed regulation. The research should, due to feedback design of the electronic regulation, together with understanding the adhesion mechanism and knowledge of its limit values, contribute to application of this kind of drive system at low-floor vehicles with independently rotating wheels.

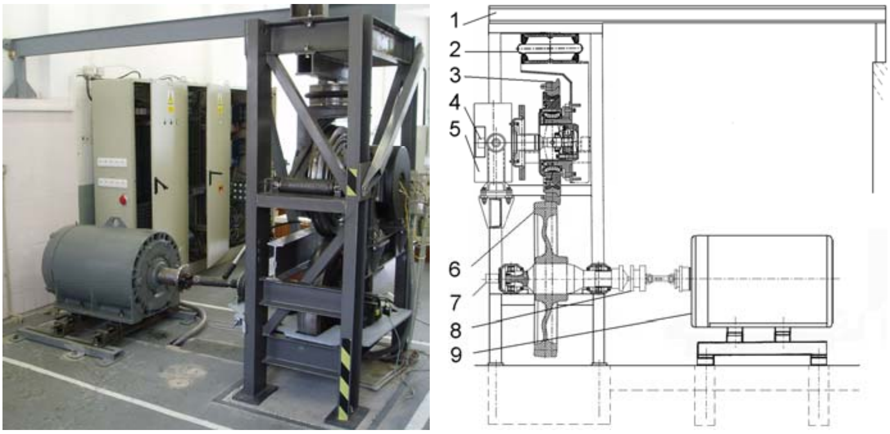

Fig. 1 *Actual configuration of the test stand*
Obr. 1 *Aktuální konfigurace zkušebního stavu*

2. The experiment results of two separate parts of adhesion characteristics

The experimental results form the testing operation is shown. Two kinds of experiments were especially carried out at the test stand: adhesion limit achievment under various conditions, and transition between traction and motor-braking modes, i.e. transition into the opposite quadrant of full adhesion characteristics.

At the beginning of each experiment, braking moment (moment of the loading motor) was set to a value that was estimated on the base of vertical load and slip and that makes a coefficient of adhesion corresponding to a standard traction mode. Then the moment was regulated to follow an increasing linear ramp until the adhesion limit was achieved and a significant rise of slip was detected. The simulation of adhesion limit achievment was performed at various speeds and under conditions of both dry and slippery surfaces (***Fig. 2***). Let us focus at measurement recordings.

The first part describes achievement of adhesion limit between the surfaces in contact. At the speed of 15 km/h, adhesion coefficient value of μ = 0,2 was reached. The value increased to 0,3 in subsequent experiments, which results from increase of friction coefficient between the surfaces having been cleaned by rolling and slipping. A measurement at 40 and 60 km/h was conducted after producing a greasy layer on both wheels. Achieved adhesion coefficient decreased notably, and that to the almost same value at both speeds, μ = 0,12÷0,14. These values can presumably be considered maximal under such surface conditions. The surfaces were carefully degreased before another experiments were carried out. At 15 km/h, the adhesion characteristics peak gradually moved upwards, up to the highest adhesion coefficient achieved, below 0,4. In authors‘ opinion, increase of the adhesion limit can be accounted for by the assumption that each slippage cleans the surfaces to some extent. Adhesion limit of μ = 0,44÷0,48 was recoreded at speeds of 40÷60 km/h.

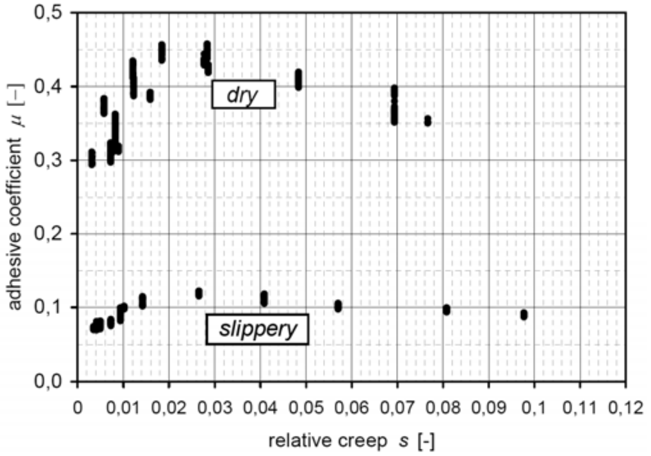

***Fig. 2** Measured adhesion characteristics for a dry and a slippery surfaces (60 km/h)*
***Obr. 2** Naměřené adhezní charakteristiky pro suché a znečistěné povrchy (60 km/h)*

Next, ascending branch of measured adhesion characteristics was analysed. The ascending branch was approximated by a linear function. Ranges of its steepness at various speeds and surface conditions are given by ***Fig. 3***. Measured steepness amounts are as follows:

$c_{\mu s}$ = (0,14÷0,27)·10^2 slippery surface,

$c_{\mu s}$ = (0,35÷0,60) 10^2 dry surface.

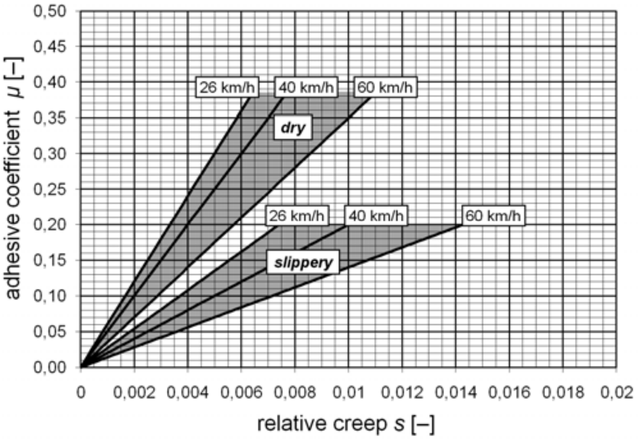

***Fig. 3** Steepness ranges for various speeds and surface conditions (DFJP 2008, 2009)*
***Obr. 3** Rozsahy strmostí pro různé rychlosti a stavy povrchu (DFJP 2008, 2009)*

Steepness values of adhesive characteristics were determined from results of the experimental simulations of traction/brake transition, too. Following values of linearized relation steepness were obtained in the area of very small slip (0,5 %):

$c_{\mu s} = 0{,}14 \cdot 10^2$ slippery surface,

$c_{\mu s} = 0{,}35 \cdot 10^2$ dry surface.

Next figure (***Fig. 4***) gives comparison of our measured ranges to results of experiments conducted by Čáp at the University of Žilina in 1975÷1982 [2] and to results of other authors. Among other conclusions, it was confirmed that the ascending branch steepness is significantly smaller than that according to Kalker's original theory [3]. Kalker himself admitted that the elasticity of bodies in contact and the slip are influenced by actual surface conditions [4]. Condition of surfaces, being not fully ideal, has an effect on actual slip amount, so that characteristics steepness is substantially smaller. Consider now the descending branch of adhesion characteristics. It is a curve that joins the curve of friction coefficient at full sliding after the peak of adhesion characteristics. Many 20th century authors gave account of the ascending section only and less attention was paid to its continuity with the friction characteristics. Freibauer's theory of relationship between adhesion and friction mechanisms in the wheel/rail contact area was confirmed at the model experimental stand of VŠDS (College of Transport and Communications) in Žilina, Slovakia. The experiments contributed to determining the value of steel surface elasticity constant which acts in formula describing the adhesion mechanism, namely $K = 2 \cdot 10^{13}$ N.m^{-3}.

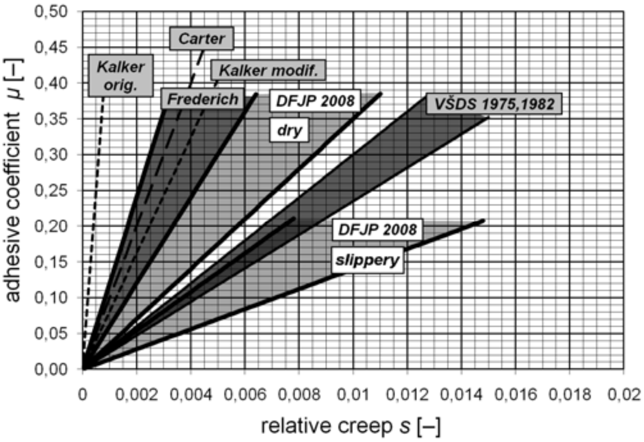

Fig. 4 *Measured steepness ranges in comparison to other authors' results*
Obr. 4 *Naměřené rozsahy strmosti v porovnání s výsledky jiných autorů*

It is necessary to find a function dependence of actual friction coefficient on creep velocity *w*. Investigating the dependence in rail vehicles' operation is not possible, since such a mode of wheel/rail contact leads to high wear. An exponential function (1) was chosen to represent the friction characteristics. Connection of adhesion characteristics and friction characteristics behind the adhesion curve's peak is the significant aspect of theory [1]. The descending (friction) branch can generally be approximated by an exponential function

$$\varphi = a \cdot e^{-b \cdot w} + c \qquad [1;\ \mathrm{m/s}] \qquad (1)$$

Coefficients *a*, *b*, *c* are obtained experimentally. Sum of the coefficients *a* + *c* gives the maximal value of friction coefficient at zero speed. The function including numerical values of its parameters, determined at the test stand of VŠDS in Žilina in the 1980s, follows:

$$\varphi = 0{,}395 \cdot e^{-0{,}75w} + 0{,}125 \qquad [1;\ \mathrm{m/s}] \qquad (2)$$

The analysis was repeated at the stand at the Jan Perner Transport Faculty, University od Pardubice, described above, in years 2008 and 2009. The existing theory [1] was confirmed. Approximation curves with and without the term *c* are situated closely together, certain difference between them shows at higher slip velocities. The approximation function was thus chosen in a form

$$\varphi = a \cdot e^{-bw} \qquad [1;\ \mathrm{m/s}] \qquad (3)$$

Following sets of data were available to us and were used for comparison:

- approximating function of Rabinowicz and Kragelskij [5];
- measurements of ERRI [7] at 25÷120 km/h;
- measurements at the model stand of VŠDS, Žilina, dry surfaces, at 3÷9 km/h;
- measurements at the DFJP test stand, dry surfaces, at 26÷60 km/h;
- measurements at the DFJP test stand, surfaces contaminated with grease, at 15÷60 km/h;

Tab. 1 *Coefficients a, b – mean values*

Tab. 1 *Hodnoty koeficientů a, b*

	a	*b*
Rabinowicz, Kragelskij	0,516	0,544
ERRI	0,420	0,196
VŠDS	0,517	0,680
DFJP, dry surface	0,480	0,280
DFJP, slippery surface	0,192	0,347

Only the ineffective part of adhesion characteristics data was evaluated – measured points of ascending branch were not taken into account. In case of other authors' measurements, data already approximated by adhesion curves served as input to our comparison; in case of our own measurements, sets of points recorded in experiments were used. Each data set (for one combination of input conditions and a certain speed) was approximated by an exponential function in form (3). Mean values of exponential function coefficients obtained from particular sources are summarized in ***Tab. 1***.

Comparison of steepness values given by other authors and values measured at DFJP in 2008÷2009 is illustrated by a diagram in ***Fig. 5***. All friction curves were moved to the same initial position at the y axis (φ = 0,35) for the sake of clarity of comparison.

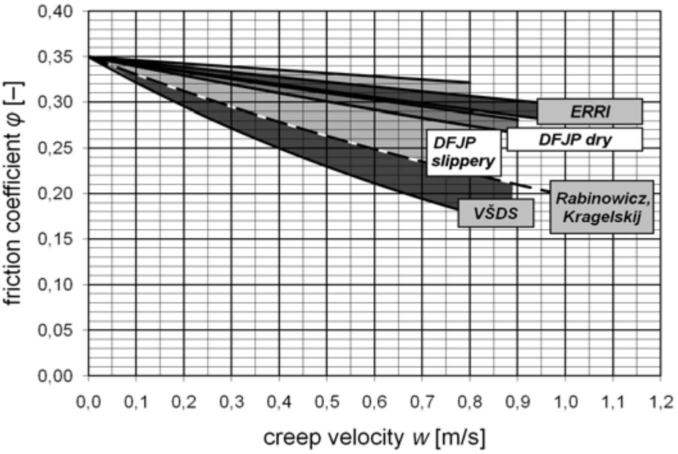

Fig. 5 *Comparison of steepness range of experimentally determined friction characteristics*
Obr. 5 *Porovnání rozsahů strmostí experimentálně získaných třecích charakteristik*

3. Conclusion

A number of experiments was conducted at the tram wheel & rotating rail experimental stand at Pardubice in 2008 and 2009 [6]. The tram wheel is driven by a permanent magnet synchronous motor. An original hardware and software equipment is employed for regulation of the motor. Two sets of experiments were carried out at the test stand. In the first set, complete adhesion characteristics were recorded and maximum values of adhesion coefficient (under two surface condition variants) were measured. The second one simulated transitions between traction and braking mode. Wheel slip was achieved by braking the rotating rail. Rotational speed of both wheels and torque transmitted from the wheel on the rotating rail was recorded. Accordance to Freibauer's model [1] was confirmed again; ranges of measured curves differ significantly neither from the model nor from other authors‘ experiment results.

Steepness of the ascending branch was determined; it is relevant for anti-slip regulation systems. The results achieved were compared to other authors‘ results that were available to us. Likewise the descending branch of adhesion characteristics which joins the friction characteristics after the peak was subject to analysis. Obtained results do not include torsional dynamics of a drive system, their validity is quasi-static. In this respect, adhesion characteristics of a synchronous motor drive appear comparable to those of other kinds of driving systems. A different behaviour of this drive type can, however, be expected in dynamical phenomena, where a great steepness of its working characteristics acts as an advantage; on the other hand, torque ripple due to permanent magnets can be expected.

Acknowledgement

This article was written with the support of VCKV (Research Centre of Rail Vehicles), funded from the project of MŠMT (Ministry of Education, Youth and Sports of the Czech Republic), reg. no. MŠMT 1M0519.

Submited: 10.4.2010

References

1. FREIBAUER, L. *Adheze kola na vozidlové dráze* [*Adhesion of wheel on track*]. Proceedings of the 7th Scientific Conference of the College of Transport and Communications in Žilina, (1983), 214-219.
2. ČÁP, J. *Strmost vzestupné větve adhezní charakteristiky* [*Steepness of the ascending branch of adhesive characteristics*]. Železniční technika [Railway Technique], 1988, No. 1/88, 12–16.
3. KALKER, J. J. *Simplified theory of rolling contact*. Delft Progress Report, Delft University Press, Ser. C, (1973).
4. KALKER, J. J. *Über die Mechanik Kontaktes zwischen Rad und Schiene* [*On the contact mechanics between wheel and rail*]. ZEV DET, (1978), No. 7/8, 214–218.
5. RABINOWICZ, E. *Friction and wear of materials.* John Wiley and Sons, New York, (1965).
6. LATA M., ČÁP J., NOVÁK, J., ČERNÝ, O., VOLTR P. *Modelování a simulace dynamiky pohonu kola synchronním motorem*. Objednatel: Škoda Transportation s.r.o., úkol č.6. Celková zpráva číslo: U6-01/2009. 48s. VCKV, ZČU v Plzni. Projekt MŠMT 1M0519. Univerzita Pardubice, DFJP UPa, (2009).
7. *Adhesion of locomotives from the point of view of their construction and operation*. UIC technical reports, Sector B 44, reports RP 9, RP 10, Utrecht, (1971).

Resumé

NOVÉ PRAKTICKÉ VÝSLEDKY MĚŘENÍ ADHEZNÍCH LIMIT ZÍSKANÉ NA EXPERIMENTÁLNÍM STAVU

Michael LATA, Jaroslav ČÁP, Petr VOLTR

Pojem adheze v oboru kolejové dopravy představuje schopnost přenosu tažné síly mezi kolem a kolejnicí. Adhezní charakteristika je vlastností mechanismu přenosu tečných sil mezi kolem a kolejnicí a představuje závislost tažné síly T nebo adhezního součinitele μ na skluzové rychlosti w, nebo v podílu k rychlosti jízdy na relativním skluzu s.

Značný význam má vzestupná oblast adhezní charakteristiky, která je zároveň jedním z nejdůležitějších vstupů regulačních systémů. Je zapotřebí stanovit hodnotu počáteční strmosti c_{Ts}, resp. $c_{\mu s}$, která se definuje jako přírůstek tažné síly, resp. součinitele adheze, vztažený na malý přírůstek relativního skluzu. Neméně významná je znalost sestupné větve adhezní křivky. Dokonalé poznání souvisejících jevů i limit obou částí adhezní charakteristiky umožňuje efektivní využití trakčních a brzdicích schopností vozidla.

V příspěvku je uveden popis experimentálního stavu tramvajového kola poháněného synchronním motorem a experimentů, které na něm autoři provádějí. Pozornost je věnována výsledkům experimentálního výzkumu v oblasti identifikace parametrů vzestupné a sestupné větve adhezní křivky. Článek tyto výsledky shrnuje a porovnává je s výsledky jiných autorů.

Summary

NEW PRACTICAL RESULTS ABOUT ADHESION LIMITES OBTAINED FROM EXPERIMENTAL STAND TESTING

Michael LATA, Jaroslav ČÁP, Petr VOLTR

The concept of adhesion in the field of rail transport represents an ability of tractive force transmission between wheel and rail. Adhesion characteristics is a property of tangential forces transmission between wheel and rail and represents the dependence of tractive force T or adhesion coefficient μ on creep velocity w, or, divided by speed of travel, dependence on relative creep s.

The ascending branch of adhesion characteristics is of great importance and acts as one of significant input parameters to drive regulation systems. It is needed to determine value of initial steepness (c_{Ts} or $c_{\mu s}$) which is defined as an increment of tractive force or adhesion coefficient, respectively, related to a small increment of relative creep. Knowledge on the descending branch is no less important. Thorough understanding of related phenomena and limits of both parts of adhesion characteristics enables an effective exploitation of vehicle tractive and braking abilities.

A theoretical model of the adhesion mechanism is briefly presented in the introduction to this paper. Following, description of a test stand of a tram wheel driven by a synchronous motor is given, as well as description of experiments conducted by the authors at it. Attention is paid to results of experimental research concerning identification of parameters of the ascending and the descending branch of adhesion characteristics. The paper summarizes this results and compares results of authors‘ own experiments to it.

Zusammenfassung

NEUE PRAKTISCHE ERGEBNISSE DER ADHESIONSGRENZEN GEWONNENE AUF DEM EXPERIMENTALEN TESTSTAND

Michael LATA, Jaroslav ČÁP, Petr VOLTR

Adhäsion ist ein Begriff im Bereich von Schienenverkehr, der eine Fähigkeit von Zugkraftübertragung zwischen Rad und Schiene beschreibt. Die Adhäsionscharakteristik ist eine Eigenschaft des Übertragungsmechanismus der Tangentialkraft zwischen Rad und Schiene und drückt eine Abhängigkeit von Zugkraft T oder Adhäsionskoeffizient μ auf der Schlupfgeschwindigkeit w oder auf dem Relativschlupf s aus.

Der Anstiegteil der Adhäsionscharakteristik ist von großer Bedeutung und stellt gleichzeitig einen von bedeutendsten Eintrittsparameter in Regulationssystemen vor. Es ist wichtig den Wert von Anstiegsteilheit c_{Ts}, bzw. $c_{\mu s}$ festzustellen, der als Zuwachs von Zugkraft bzw. Adhäsionskoeffizient bezogen auf kleinem Schlupfanstieg definiert ist. Die Kenntnis über dem Abstiegteil ist nicht minder bedeutungsvoll. Die präzise Erkennung der zusammenhängenden Vorgängen und Grenzen der beiden Teile von Adhäsionscharakteristik ermöglicht effektive Ausnutzung der Traktions- und Bremsvermögen von Schienenfahrzeugen.

Im Artikel wird die Beschreibung des experimentalen Tramradteststandes, der mit Synchronmotor getrieben ist, sowie Beschreibung der durchgeführten Experimente vorgeführt. Die Aufmerksamkeit wird auf die Forschungsergebnissen im Bereich der Parametererkennung der An- und Abstiegteils von Adhäsionscharakteristik gewidmet. Diese Ergebnisse werden im Artikel zusammengefasst und mit Ergebnissen von anderen Autoren verglichen.