767. The concept of transducer for detection of trackway surface condition basing on frictional coupling of wheel with a rail and its experimental verification

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Abstract. Description of design and rules of operation of transducer for detection of trackway surface condition in mine underground workings is the project objective. Information about the surface condition collected with use of the transducer will enable adaptive (depending on track surface conditions) control of breaking torque of wheels of rail locomotives and, in a result, shortening of braking distance by minimization of slippage. At first the requirements for braking systems of mining locomotives, with reference to real conditions of their operation, will be presented. Then selected braking systems, which are applied in the locomotives used in the coal mine industry, will be described with a special attention paid to the solutions, which potentially shorten the braking distance, including also the solutions based on ABS system used in the automotive industry. A concept of dedicated transducer, task of which is a continuous detection of surface condition of trackway, on which the locomotive moves, will be described with reference to the presented solutions. Transducer for detection is based on frictional coupling between its active component (so-called "tracking wheel") and a rail. Presented concept will be proved by a series of verification experimental tests. Presentation of tests results and determination of further directions of R&D work as regards discussed problems will be the summary of the project.

Keywords: frictional coupling, friction, slippage, braking, rail locomotives, trackway surface condition, tracking wheel.

Introduction

Changeable adhesion on trackways in mine workings and lack of adaptive systems for selection of braking torque in the braking systems of mining locomotives cause dangerous slippage during braking (especially during emergency braking). Analyzing the present solutions of braking systems as regards ensuring of braking without slippage, they can be divided into the systems of constant braking torque and systems equipped with detection of slippage based on ABS system used in the automotive industry [1, 2]. However, neither the first nor the second method is free of defects, which in the light of standard requirements do not eliminate slippage during braking for all possible conditions of adhesion of wheels to rails [3]. Research-and-design work on the method for current assessment of trackway surface condition, with overriding objective to ensure effective braking without slippage, has been started to meet the requirements of the standard and to increase safety of underground rail transportation. This method is based on use of phenomenon of frictional coupling between so-called "tracking wheel" of detector (specialized transducer) and rail.

Problem of braking of rail locomotives in the light of standard requirements

PN-EN 1889-2+A1:2010 Standard entitled "Machines for underground mining industry – Underground self-propelled machines – Safety – Part 2: Rail locomotives" is in force as regards safety and functionality of braking systems used in mining locomotives [3]. This Standard describes wide spectrum of problems associated with safety of operation of braking systems of rail locomotives. However, the most significant aspects from the point of view of problems discussed within conducted research work are as follows:

- equipping of locomotive with main brake (manoeuvring brake), with emergency brake and parking brake [3],
- the brakes should have characteristics of braking selected in such way to stop the train on the shortest possible distance, which corresponds to predicted friction conditions between wheels and rails at assumed load and inclination [3],
- time between initiation of main brake or emergency brake and reaching of 90 % of minimal required braking force, which should not exceed 2 seconds [3].

Record that refers to braking without slippage is the most significant from the point of view of operational safety. On the basis of information obtained from the users and designers of locomotives it results that dangerous slippage of train takes place very often during braking, especially when the train is loaded or when it moves on a big inclination. There are the following reasons of such situations:

- local adhesion disturbances, which result from contamination of rails with substances decreasing coefficient of friction (oil, hydraulic fluid, water, etc.),
- too high braking torque selected during designing of machine, which causes blocking of wheels in a situation, when coefficient of friction between wheel set and rail is decreasing.

At this point it should be emphasized that most of mining locomotives, which are manufactured at present, meet the discussed requirements. Discrepancies between certification tests and real behaviour of locomotives during operation result from the fact that the tests are often conducted in laboratory conditions where the tested track is perfectly prepared (i.e. cleaned and degreased). Due to that, a proper coefficient of friction between wheels and a rail is maintained during the tests of braking systems, what eliminates any slippage.

Making analysis of available solutions of braking systems equipped with a system protecting against slippage of wheel sets, ABS system known from automotive industry arises first at the thought [1]. The following features of this system, which are used to limit slippage during braking of mining locomotive, should be mentioned:

- minimization of time of slippage between wheel and rail [4],
- use of stepwise and smooth control of braking torque [4],
- adaptation of the method for detection of slippage of wheels consisting in measuring of difference in their speed [4].

There are the following advantages of use of ABS in mining locomotives:

- simple design of the system for detection of slippage based on a measurement of speed of wheel sets (with use of inductive transducers, incremental encoders or ABS sensors that are used in cars [1]),
- simple implementation of stepwise setting of braking torque (use of distributor of relatively fast response to control signal).

However, the requirement of “braking without slippage”, which is imposed by the mentioned standard, limits the possibility of adaptation of this system in mining rail locomotives [3]. The principle of operation of the system, which is based on elimination of slippage by cyclic brake release and braking of wheel sets till the moment of obtaining of minimal travel speed, is the main reason of this situation. During a cycle of braking of wheel sets even it is short it can lead to unexpected slippage.

It is also worth to mention one disadvantage of ABS system, which consists in lack of information about condition of the surface at the moment of starting of braking process. In such situation in most optimistic case one slippage, which is indispensable to start the operation of ABS system (in the case of adaptation of smooth control of braking torque), can take place.

Due to this, alternative methods for elimination of slippage should be considered. One of them is a method of continuous analysis of condition of trackway surface and adaptive method – i.e. follow-up control of braking torque, which ensures braking without slippage.

Frictional coupling of wheel with rail as a method for detection of condition of trackway surface

Suggested method for detection of condition of trackway surface is based on a phenomenon of frictional coupling between measuring wheel of dedicated transducer and a rail. This transducer is installed in a locomotive chassis, where its active part, which is called "tracking wheel", is placed in rail axis. Suggested method of assembly of transducer in a locomotive chassis is presented in Fig. 1.

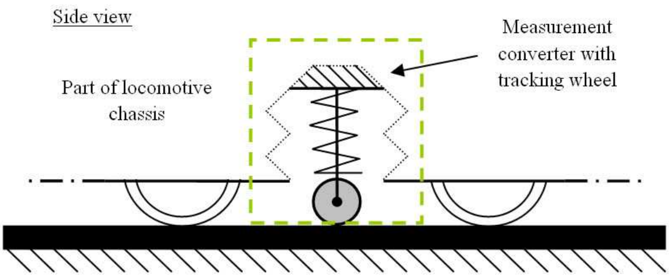


Fig. 1. Suggested method of assembly of transducer in a rail locomotive chassis [5]

Design of transducer is shown in Fig. 2 (view along the axis of the rail).

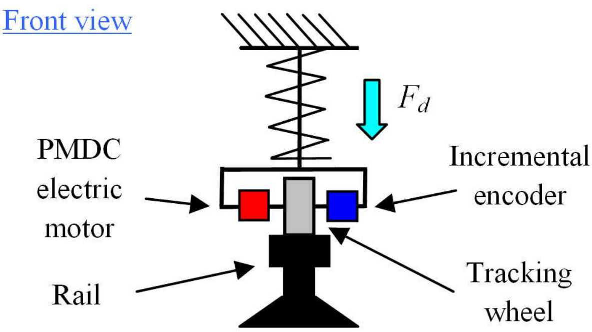


Fig. 2. Design of measuring transducer [5]

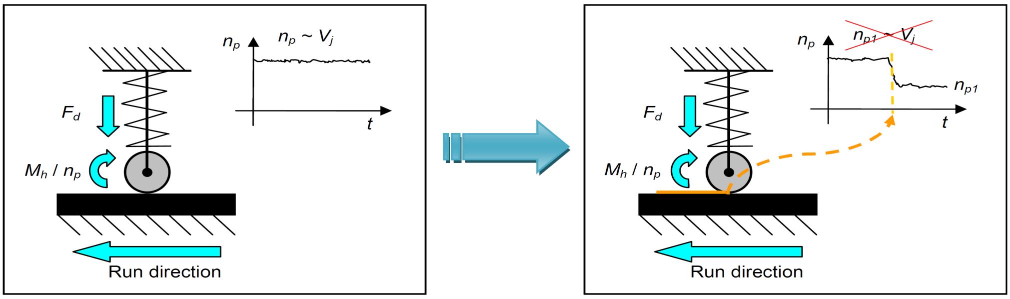
Presented transducer consists of small wheel rolling directly on the rail together with the locomotive ("tracking wheel"). DC motor and incremental encoder are both installed on the joint axle with the "tracking wheel". Generation of small braking torque is a task of electric motor. PMDC motor was used in a transducer. Continuous measurement of rotary speed of "tracking wheel" is the task of incremental encoder. All the equipment is installed in a locomotive chassis on an amortized arm, which presses the transducer to the rail surface with constant force F_d, ensuring reduction of potential unevenness of the track.

The principle of operation of transducer is as follows: during the locomotive travel electric motor generates small braking torque M_h, sense of which is opposite to the travel direction. The value of the torque is selected in such way to ensure that for proper rail surface (not covered with substances, which decrease coefficient of friction) the "tracking wheel" moves in a direction of travel of machine.

The following two cases describing condition of trackway surface will be considered to present the principle of operation of transducer in the simplest way:

- dry and degreased track,
- oily track.

Fig. 3 presents the described situations.



a) Dry track (f_1) b) Oily track (f_2)

Fig. 3. Behaviour of measuring transducer for changeable conditions of trackway surface

For both cases detection of surface condition is realized by analysis of rotary speed of "tracking wheel" in time.

In the first case (Fig. 3a), when the track is dry and degreased, for suitably selected pressing force F_d, braking torque M_h and coefficient of rolling friction f_1, rotary speed n_p of tracking wheel is proportional to speed v_j of the locomotive.

In the second case (Fig. 3b) the transducer moves on slippery section of trackway, where a coefficient of rolling friction is smaller than in the previous case $f_2 < f_1$. Then braking torque M_h, which is generated by PMDC motor, causes decrease of rotary speed of „tracking wheel".

Electronic system of transducer due to continuous analysis of changes of momentary rotary speed, on the basis of its unnatural (rapid) decrease, recognizes lowering of friction coefficient. On that basis the system detects condition of rail surface, which at the moment of locomotive braking can lead to dangerous slippage of wheel. Information signal obtained in this way can be transferred to the superior system, which controls locomotive brake, and selects value of braking torque to eliminate slippage of wheels. Suggested method for detection of surface condition eliminates basic disadvantages of classic ABS system, i.e.:

- occurrence of slippage during pulsating braking,
- it gives information about condition of trackway surface before starting of braking.

At that point it should emphasized that discussed transducer can be used only in locomotives equipped with braking system of smooth control of braking torque. Reviewing the types of braking systems (due to their control method), which are used in locomotives manufactured by the Polish producers, they can be divided in the following way (see Fig. 4) [2].

Braking systems of rail (floor-mounted) locomotives

Of constant braking torque	Of controlled braking torque
(emergency brake – parking brake)	(manoeuvring brake)

Fig. 4. Classification of braking systems of mining locomotives [2]

Presented classification of braking systems results from the requirements of the standard, mentioned in this paper [3]. Mainly multi-disc brakes are used as the brakes of constant braking torque [1]. The brakes of controlled braking torque (manoeuvring brake – main brake) use hydraulic motor, which during braking starts to operate in a pumping mode. Control of braking torque is realized by changing of capacity by the controlled proportional valve [1]. There are the following examples of locomotives in which both mentioned types of braking systems are used [2]:

- Diesel drivetrain of SKZ–81 floor-mounted railway (manufactured by Ryfama, JSC),
- Lds–31 EM underground electric locomotive (manufactured by Energo-Mechanik, Ltd.),
- Lds–100K–EM (A) underground diesel locomotive (manufactured by Energo-Mechanik, Ltd.).

All presented types of vehicles were designed at the KOMAG Institute of Mining Technology [2]. Thus, transducer can be adapted for cooperation with manoeuvring brakes – main brakes of the mentioned types of machines. Due to the necessity of proper operation of electronic sub-systems of machine to ensure proper operation of transducer, the transducer can not support emergency brake. Despite of this, it can participate in so-called combined braking, which in the case of sudden braking uses the main brake, not emergency brake. Due to that it is possible to control braking torque adequately to conditions on a track.

Verification of accepted method for detection of condition of trackway surface

A series of initial tests was conducted to verify accepted method for detection of condition of trackway surface. The tests were focused on contact phenomena between rail and wheel of the measuring transducer. A special test rig, diagram of which is presented in Fig. 5, was designed for that purpose.

It was equipped with a steel disc, on the surface of which a path simulating trackway rail was installed. Due to limited technical possibilities, plane motion was replaced by a rotary motion. Tested measuring transducer – “tracking wheel” – moves on the path surface. A disc is driven by a gear through the motor M. Rotary speed of the motor is controlled by a frequency converter. Incremental encoder, which measures rotary speed of path, was installed on its axis. A prototype of transducer was installed on the path surface. According to the concept it consists of rolling wheel, which is axially connected with DC motor and incremental encoder. Rotary speed of “tracking wheel” is measured by incremental encoder. Electric motor, task of which is a generation of braking torque M_h, is supplied from DC feeder. Braking torque is controlled by a setting of AC adapter current limit. The time when braking torque is applied to the “tracking wheel” is measured indirectly through amount of voltage at contacts of SW switch in the motor supply circuit. A motor obtained from a drive of head of Hewlett-Packard inkjet printer was used in the test stand.

The transducer was installed above the path on an amortized arm, which was equipped with smooth control of pressing force. The control was realized by the screw pressing the spring. Transducer pressing force F_d is measured by a strain gauge force transducer placed between spring and component that fixes the transducer. Identification of position of places contaminated with substances decreasing or increasing friction coefficient was realized by an inductive transducer (proximity transducer) and steel marker on a side surface of the disc.

Acquisition of measuring data was realized by 8-channel SPIDER-8 measuring amplifier manufactured by HBM Company, connected with a PC computer. Measuring process is controlled using CATMAN® software.

A developed model of test stand is presented in Fig. 6.

Initial tests results

Initial tests were carried out to verify suggested method for detection of condition of trackway surface. They were presented for two aforementioned cases of track surface conditions i.e.:

- dry track (cleaned and degreased),
- track evenly covered with Hipol Mineral oil.

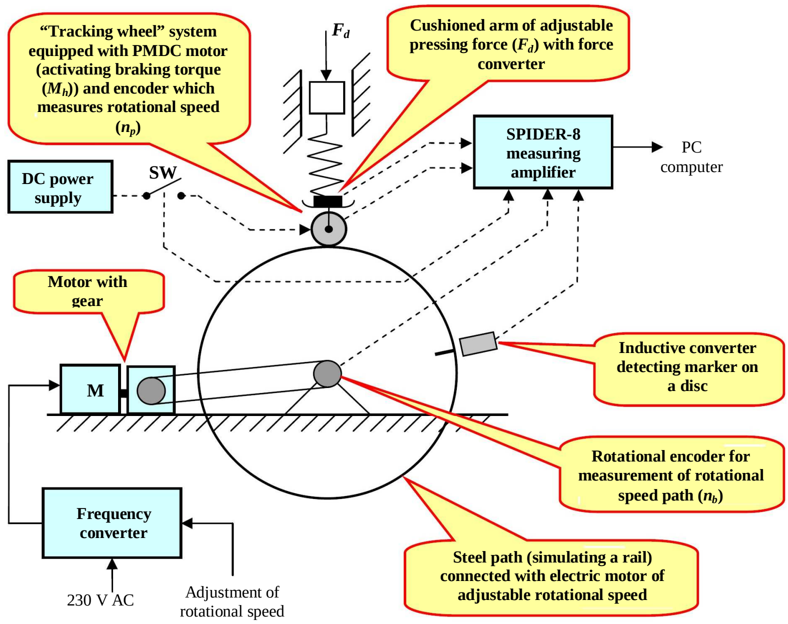


Fig. 5. Block diagram of test rig for testing frictional coupling rail – wheel

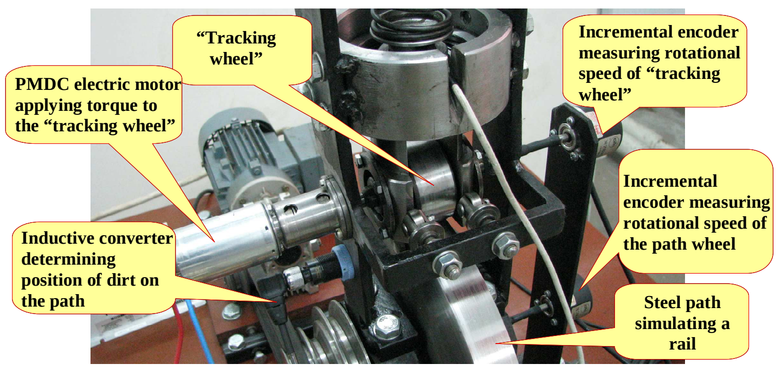


Fig. 6. View on the "tracking wheel"

The tests were carried out for two forces pressing the transducer to path F_d equal to 16 and 60 N. During tests the motor current generating braking torque was equal to 1.5 A (rated value of used motor).

Rotational speed of path n_b and "tracking wheel" n_p, as well as force pressing the converter to the path F_d and condition of the perimeter of motor generating braking force are registered.

In Fig. 7, 8 and 9 time processes obtained during tests were given. Hatched areas mean time intervals in which braking torque M_h is applied to "tracking wheel".

After analysis of the above diagrams we can conclude that in the case of dry track (cleaned and degreased) application of braking torque did not cause significant changes in speed of "tracking wheel" in the selected range of changes of path rotational speed (30 ÷ 130 rpm).

In the case of oiled track (evenly covered with oil film) application of braking torque caused significant reduction of rotational speed of the "tracking wheel". This indicates for slips of the transducer wheel, what means reduction of rolling friction coefficient.

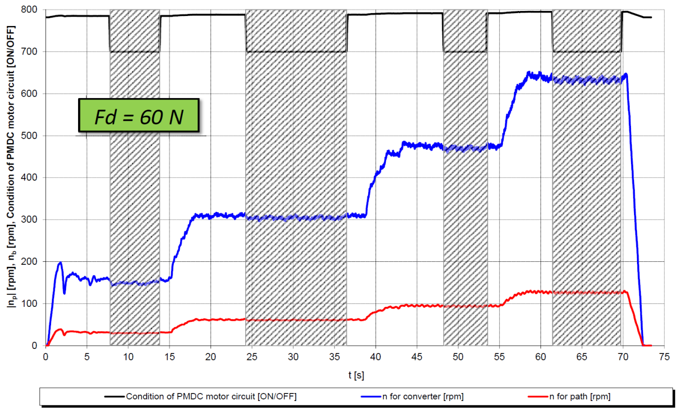


Fig. 7. Diagram of rotational speed of the "tracking wheel" n_p for four path speeds n_b for dry track (F_d = 60 N, I_M = 1.5 A)

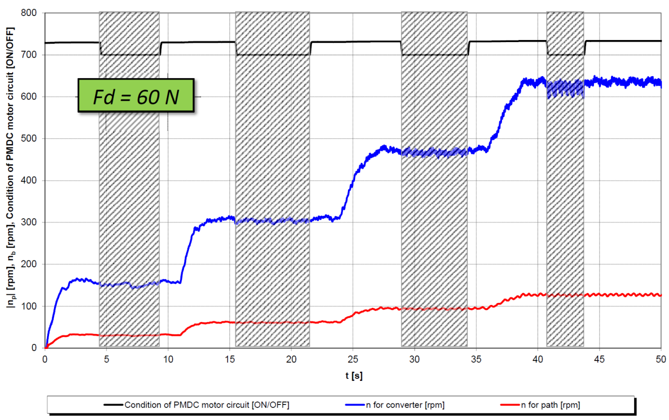


Fig. 8. Diagram of rotational speed of the "tracking wheel" n_p for four path speeds n_b for oiled track (F_d = 60 N, I_M = 1.5 A)

Level of reduction of rotational speed of the "tracking wheel" during tests on oily track strongly depends on force value pressing the transducer to the rail F_d. On the basis of obtained relationships it can be seen that with reduction of the pressing force the drop in rotational speed increases.

Both in the case of testing the system at pressing force F_d equal to 60 N and 16 N (oiled track), drops in rotational speed were observed for high rotational speeds (travel speeds).

Additionally it was found that reduction of the pressing force F_d causes extension of slippage detection range to greater range of "travel speed" (path rotational speed).

Summary

The problem of detection of trackway surface condition can be a starting point for further studies on elimination of potential hazards associated with locomotives slippage. On the basis of normative requirements for braking systems of locomotives as well as on the basis of technical theoretical grounds, the method for detection of trackway surface condition was developed basing of the phenomenon of frictional coupling between rail and wheel. Continuous analysis of friction coefficient is main advantage of the presented method regardless whether the machine accelerates, moves with uniform motion or brakes. That gives advancing information about condition of track surface to the supervisory brakes control system, which can earlier select the proper parameters of braking system operation. To verify efficiency of the developed method, a special testing facility was designed. On the basis of the results, the proper efficiency of the developed detection method was confirmed. The comparative tests (for the same braking torques M_h and the same rotational speed of the path) showed a significant reduction of rotary speed of "tracking wheel" in the case of moving on oiled track. Besides, the results showed the necessity of further research on extension of range of detection to the entire range of travel speeds.

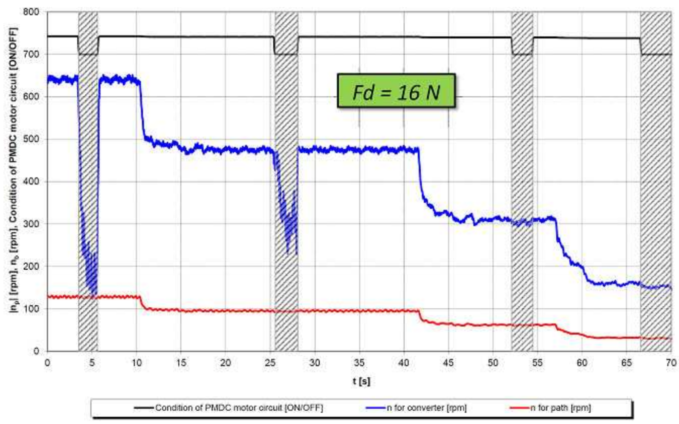


Fig. 9. Diagram of rotational speed of the "tracking wheel" n_p for four path speeds n_b for oiled track (F_d = 16 N, I_M = 1.5 A)

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