Mechanical Systems and Signal Processing 111 (2018) 265–284

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

A new adaptive slip-slide control system for railway vehicles

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ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form 23 January 2018
Accepted 23 March 2018

Keywords:
Vehicle dynamics
Traction system
Slip-slide control
Adhesion
Real-time system identification
Health monitoring

ABSTRACT

In railway transport, braking and traction forces mainly depend on the normal force and the adhesion coefficient between the wheel and the rail. Regarding the restrictions on controlling the normal force, maximization of adhesion coefficient seems to be the only way of increasing braking and tractive efforts. Moreover, efficient utilization of adhesion can also reduce operating costs with avoiding early wheel and rail damages and minimizing the trip time. On the other hand, adhesion between the rail and the wheel is a highly dynamic function of many parameters such as environmental conditions, speed and slip ratio. Unfortunately, there is not any sufficiently accurate and reliable way of obtaining these parameters yet. Recently, an event based control scheme has been presented to maximize adhesion utilization without necessitating any of the above-mentioned parameters. This method provides efficient utilization of adhesion and eliminates problems (e.g. reliability, stability, continuous excitation of traction system and slow recuperation detection time) that are faced with the previously developed approaches. In this paper, dynamics of phase shift between the input and the output of the traction system is analyzed and an adaptive form of the recently proposed event based control scheme is constructed in order to further develop the adhesion utilization. Results obtained with the adaptive approach are compared with the conventional form of the control scheme as well as experimentally proven and industrially applied two successful methods for different driving scenarios and wheel-rail conditions.

1. Introduction

Due to countless benefits it provides, railway transport is a major form of passenger and freight transport in many countries. Although railway vehicles have less problems compared to their alternatives, there are still many technological issues which need to be solved for more reliable and affordable way of transportation. Slip and slide problem is one of these issues that results in insufficient braking and/or traction performance as well as early damages in rails and wheels.

Railway vehicles use adhesive forces between the wheels and the rail to be able to obtain the required tractive and braking efforts. Adhesion, nevertheless, is a highly complicated phenomenon that depends on many factors including surface properties, material types, temperature and velocity. However, experimental results show that for each specific combination of these factors, there is an optimal slip ratio that maximizes the adhesion force between the wheel and the rail. Fig. 1 (which will be attained in the third section) shows the changes in adhesion coefficient in relation to changes in slip ratio and velocity.

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https://doi.org/10.1016/j.ymssp.2018.03.050

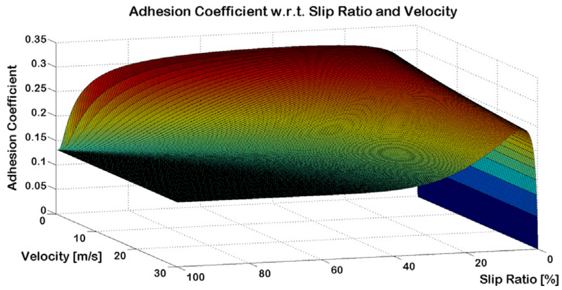

Fig. 1. Adhesion coefficient with respect to slip ratio and velocity.

As it can be seen from the figure, for each velocity value, there is an optimal slip ratio which maximizes adhesion without excessive slip. The aim of the slip and slide control system is holding the slip ratio at this optimal value.

Unfortunately, neither attaining an accurate slip ratio nor deriving the optimal slip ratio for a specific velocity and environmental conditions is a simple task. Slip ratio can be defined as the ratio of relative velocity, between the wheel and vehicle velocities, to the wheel velocity (traction case) or to the vehicle velocity (braking case). Hence, the performance of the slip ratio acquisition is directly related to the integrity of vehicle velocity information.

Many methods have been tried to obtain the railway vehicle velocity before. One such method is the usage of radar/lidar sensors in measuring the velocity of the train. Although these sensors are very accurate in velocity measurement, they are very expensive and sensitive to environmental conditions (fog, rain, snow, etc.).

Another way of acquiring velocity information is the usage of GPS signals. There are many well-known techniques in literature that combine GPS information with other sensors such as the wheel speed sensor, the accelerometer and the inertial measurement unit [1]. Unfortunately, these methods are not reliable enough since the availability of a GPS signal is not guaranteed.

Beside the efforts to measure vehicle velocity directly, researchers have also tried to attain this information using indirect methods and different estimation approaches. One of these methods is based on detection of excitations resulted from track irregularities with acceleration and angular rate measurements at different wheelsets and measurement of the time shift between dynamic responses of two wheelsets with respect to the same irregularity [2]. In another study [3], vehicle velocity is tried to be estimated with soft computing techniques which use comparison analysis of longitudinal velocities of different wheels. Additionally, there are observer based approaches to estimate this information [4–6]. Nevertheless, slip and slide control systems based on vehicle velocity acquisition do not satisfy the safety concerns of industrial applications and necessitate an additional estimation procedure for optimal slip ratio derivation.

Lack of a sufficiently accurate and reliable method to obtain vehicle velocity leads researchers to search for alternative approaches. In one of these studies, a comparison of motor current measurements from different axles is used for the detection and control the slip-slide situations [7]. However, using the speed measurements in slip-slide control instead of the current differences still provides better performances. Hence, many of the experimentally proven and industrially applied successful methods use only wheel speed information in this control task. The simplest approach to control slip-slide situations might be using the wheel speed information of different axles together. Suppose that one of the axles is in slip/slide situation. Since this axle turns faster/slower than the other axles in this special case, detecting and controlling the slipping/sliding axle is an easy duty if the wheel speed information of all the axles is available. Nonetheless, this method fails when all of the axles slip/slide at the same time. Although using a trailer axle can solve this problem, all-wheel-drive vehicles like locomotives do not let us use this simple solution.

Some of the researchers tried to construct "trustable axle" to overcome this problem. In one of these approaches, when the wheelsets accelerate higher than a predefined threshold, one of them is chosen as the trustable wheelset and the reference torque of this wheelset is decreased sharply until the adhesion state returns back to the so-called "micro slip area" [8]. Then this axle is used as a reference axle and the adhesion forces on the other axles are tried to be maximized using its wheel speed information. Despite the fact that this method efficiently solves the slip-slide problem, it is not yet the optimum one since the adhesion utilization of trustable axles can be increased.

An interesting idea for slip-slide control is based on torsional analysis of traction system [9]. It is proposed that the excessive slip/slide situations induce torsional vibrations on the traction system at its natural frequencies. A close inspection of these vibrations is used in control scheme to utilize adhesion more efficiently. Similarly, spectrum analysis of rolling noise might give a clue about the slip and slide problem [10]. Nevertheless, these methods are not reliable enough for industrial applications. Soft computing methods can provide alternative solutions for the problem, even though they do not provide satisfactory performances [11].

Certainly, an accurate estimation of adhesion force between wheel and rail could be very beneficial for the solution of the slip-slide problem. To this end, disturbance observer based on the traction model of the railway vehicle is frequently applied in adhesion control systems. One of the first examples of this approach is using the output of the disturbance observer to obtain the derivative of the adhesion coefficient with respect to the slip ratio [12]. The control strategy tries to hold this