

# Detection and Estimation of Slip Effect on the Parameters of DC Motor Mounted on Commuter Rail using Kalman Filter: A Feasibility

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**Abstract:** The paper proposes the technique of detection and estimation of slip by using parameters of motor such as torque and current for a locomotive system. The motor is used for controlling wheel-set motion mounted on each axle of the rail. As the track condition changes (due to decrease in adhesion/friction), the parameter of motor considerably varies resulting slip occurrence. By utilizing inertial mounted sensors (such as tachometer) in order to measure the velocity of the train, slip can be detected. Furthermore, the estimation of motor parameters is carried out using Kalman filter, which minimizes the usage of additional sensors. In this regard, the proposed method offers a cost effective, accurate and robust solution for the slip issue in order to avoid accidents in locomotive systems. The technique is validated using simulation results in this paper.

**Keywords:** Locomotive, Slip, Detection, Estimation, Kalman Filter, Rail.

## I. INTRODUCTION

Low adhesion (friction) problem has been spotted a vital parameter to be considered from the beginning of railway transportation for the designing and operation of railway vehicles [3]. The weather effect especially autumn drastically disturbs the adhesion level in which decomposed leaves are crushed by the wheels of the train. In this condition, applying a higher force on the track by the wheel cause wheels-slip during traction and it is subjected to slide while braking, which may be responsible as the damage of track and wheels itself. Various techniques are adopted around the world to overcome this issue, the few of them used (temporarily) are as: (i) vegetation, (ii) sandites (iii) water jetting management [2]. Hence from these methods, the designers still could not get the comprehensive results in order to reduce the adhesion because of the highly non-linearity of adhesion variations most of the time. Therefore, it is difficult to monitor and calculate it exactly and it may certainly desire some level of technical expertise to introduce a solid and appropriate technique to deal with this problem.

In this paper, a wheel-set model is under observation and assessment is made on the basis of comparison between its dynamics under stable condition and slip condition. The information of slip can be acquired from motor parameters such as torque/current connected with the each axel of rail as shown in Fig. 1. In addition Kalman filter is used in order to get the accurate

estimation of torque/current. Once torque/current is estimated we can ultimately measure that how much slip is occurred during traction. The remaining paper such as section II comprises of rail wheel-set. Section III presents the modeling of system dynamics. Section IV states the details of estimation of slip using Kalman filter. Section V shows the simulation results. Finally section VI concludes the proposed method.

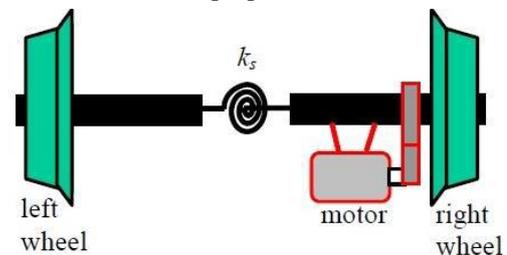


Fig. 1 Motor mounted wheel set: Courtesy to [9]

## II. RAILWAY WHEEL-SET

The essential element of the railway transport is wheel-set rolling on the railway track. Its dynamics highly affect the transport comfort, the wear of rails and the life time of both wheels-set and track [1]. Wheel-set dynamics are highly affected by the variations in adhesion level between wheel and track due to different contact conditions [7].

These contact conditions are highly nonlinear in respect of creep forces generated at wheel-rail interaction. Fig. 2 shows the variation in the adhesion coefficients and creep forces. It also shows the presence of any kind of contamination, e.g. crushed leaves, icing, liquid (water) etc. This causes substantial rise and fall in

the level of friction between wheel and track. In order to get proper traction and braking performance, the lowest level of adhesion must be kept (i.e., 0.25 for traction and 0.1 for braking).

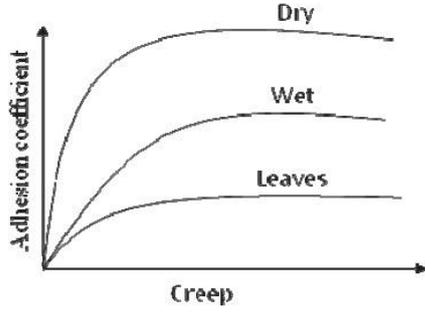


Fig. 2: Adhesion Curves: Courtesy to [3]

### III. MODELING OF SYSTEM DYNAMICS

#### A. Bogie Configuration

Bogie configuration is a mechanical configuration commonly found in rails. In this regard, each bogie consists of two wheel-sets. Those wheel-sets have two wheels fixed in a single axel, by which both wheels rotate at same angular velocity.



Fig 3: Wheelset arrangement in a bogie: Courtesy to [5]

#### B. Dynamic Equations of Wheel-Set

Motor drives the right wheel by applying torque which is denoted as  $T_t$ , the other rotational dynamics can be given as:

$$I_R \dot{\omega}_R = T_t - T_K - T_R \quad (1)$$

$$I_L \dot{\omega}_L = T_k - T_L \quad (2)$$

$$\dot{\theta}_K = \omega_R - \omega_L \quad (3)$$

Where,  $I_R$  is moment of inertia of right wheel,  $\dot{\omega}_R$  is angular velocity of right wheel,  $T_k$  is torsional torque produced by axle stiffness,  $T_R$  is the right wheel tractive torque,  $T_L$  is the left wheel tractive torque,  $I_L$  is moment of inertia of left wheel,  $\dot{\omega}_L$  is angular velocity of left wheel,  $\dot{\theta}_K$  represents the torsional angle of the axle.

$$T_R = r_0 f_{11} \lambda_{XR} \quad (4)$$

$$T_L = r_0 f_{11} \lambda_{XL} \quad (5)$$

$r_0$ , is the wheel radius,  $f_{11}$  is available adhesion

$$\lambda_{XR} = \frac{r_0 \omega_R - v}{v} \quad (6)$$

$$\lambda_{XL} = \frac{r_0 \omega_L - v}{v} \quad (7)$$

Replacing  $T_R$  and  $T_L$  in equation 1 and 2 yield following wheel set model

$$\begin{bmatrix} \dot{\omega}_R \\ \dot{\omega}_L \\ \dot{\theta}_s \end{bmatrix} = \begin{bmatrix} -\frac{r_0^2 f_{11}}{v I_R} & 0 & -\frac{k}{I_r} \\ 0 & -\frac{r_0^2 f_{11}}{v I_L} & -\frac{k}{I_L} \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \\ \theta_s \end{bmatrix} + \begin{bmatrix} \frac{1}{I_R} \\ 0 \\ 0 \end{bmatrix} T_t \quad (8)$$

From Above mentioned state space model, it can be observed that the wheel-sets dynamics depends on the available adhesion and vehicle speed. Therefore, these factors cannot be ignored when we are considering stability, ride comfort and safety of the vehicle. Low adhesion level can cause slip during traction and slide during braking.

### IV. DETECTION AND ESTIMATION OF SLIP

#### A. Detection of Motor Torque/Current

Proposed technique for slip detection through motor torque estimation is a versatile and cost-effective, eliminates need of extra sensors. With the help of internal mounted sensor for finding vehicle velocity, slip can be observed by transforming linear velocity into angular velocity of the wheel.

Armature control DC motor provides a great assistance to control the speed of train, especially where high starting torque is required. Typically motor is installed on one side of axel as shown in Fig. 4, connected on right wheel so it acts as driving wheel while the left wheel is moved on the torsional torque of the axel rigidly fixed with right wheel (see Fig. 4 for details).

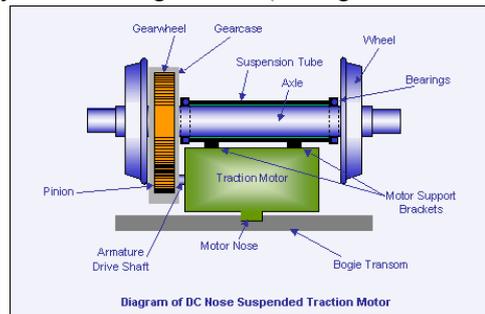


Fig. 4 Motor Mounted Wheel-Set [<http://www.railway-technical.com/drives.shtml>]

In armature control DC motor, torque is directly proportional to current

$$T \propto i_a \quad (9)$$

In this situation, when slip occurs, wheels rotates freely, as a result significantly the load from motor reduces hence motor torque and current falls down. We can easily measure motor current /torque consequently we can estimate wheel slip indirectly.

### B. Kalman Filter Design for Estimation

Kalman filter can be used when the process of estimating or obtaining the best estimate from the noisy data including the elimination of undesired signal, which in this case are noise variables. It processes observations to yield an estimate of a variable of interest, which optimizes a certain criterion. So, a proper estimate of the system parameters is needed to extract the right information and then enhance it. Kalman filter is ideal for linear stochastic systems that are why it is of our interest for the proposed approach [8].

Consider the DC motor model given in the equation below which may be written in the following standard forms

$$X(t) = Ax(t) + Bu(t) + w(t) \quad (10)$$

$$Y(t) = Cx(t) + Du(t) + V(t) \quad (11)$$

where  $x(t)$ , is the actual state vector,  $u(t)$  is input vector,  $w(t)$  is the process noise applied by the track irregularities  $v(t)$  is the inertial noise or noise level of the sensor,  $y(t)$  is the output vector. Sensor already provided in the vehicle for the measurement of velocity of the train, have been found to offer satisfactory results for the designing of Kalman filter as input from the system (Model).

$$\frac{d}{dt} \begin{bmatrix} \theta \\ i \end{bmatrix} = \begin{bmatrix} -\frac{b}{j} & \frac{k}{j} \\ -\frac{K}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} \theta \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} V + w(t) \quad (12)$$

$$y = [1 \quad 0] \begin{bmatrix} \theta \\ i \end{bmatrix} + v(t) \quad (13)$$

It is considered that measurement and process noise has no relation. The equations for Kalman filters are given as

$$\hat{x}(t) = A\hat{x}(t) + Bu(t) + K[Y(t) - C\hat{x}(t)] \quad (14)$$

$$k = PC^T R^{-1} \quad (15)$$

$$\dot{P} = AP + PA^T - KKK^T + Q \quad (16)$$

In above equation  $-1$  superscript indicates matrix inversion and subscript  $T$  indicates transposition of matrix.  $\hat{x}$  shows the estimated state vector and  $K$  is Kalman filter gain, to weight the measurement innovation  $Y(t) - C\hat{x}(t)$ . Where  $P$  is the estimation error covariance which depends upon the selection of measurement noise covariance  $R$  and the process noise covariance  $Q$  and  $R$  can be calculated by the following equations

$$Q = E[ww^T] \quad (17)$$

$$R = E[vv^T] \quad (18)$$

$$Q = 0.001$$

$$R = 0.00000000001 * \text{eye}(2)$$

Is taken

## V. SIMULATION RESULTS

### A. Simulation of Wheel-sets

The simulation results shown in Fig. 5 given below are for wheel-set model and taken for 10 secs. For initial 5 secs, the adhesion level of surfaces supposed to be dry. So that, it can be observed that the speed of left wheel and right wheel are nearly constant but the vehicle velocity is increasing linearly. After the specified time e.g.,  $t=5\text{sec}$ , the wheel rail contact condition is changed from dry case to poor case (contaminated leaves) causing slip occurrence. As a result, wheels move freely, significant speed of left and right wheel abruptly change. On other hand, after 5 secs, vehicle speed remains almost constant.

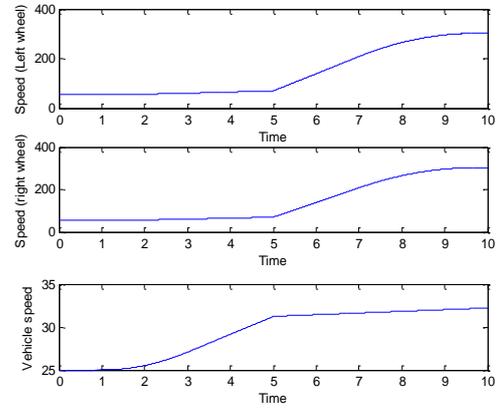


Fig.5: wheel set simulation Results

### B. Simulations on the Effect of Slip on Motor Parameters

Motor Torque and RPM variations can be observed in favor of previously mentioned time for each track condition as per applied tractive effort from the Fig. 6 to 8 below. As after 5 secs, the track conditions changes from dry condition to poor condition, forcing slip to occur. Load on the motor consequently reduces making the current also on the decrease. On the other side, RPM of motor increases significantly because the slip causes motor rotate freely with higher RPM.

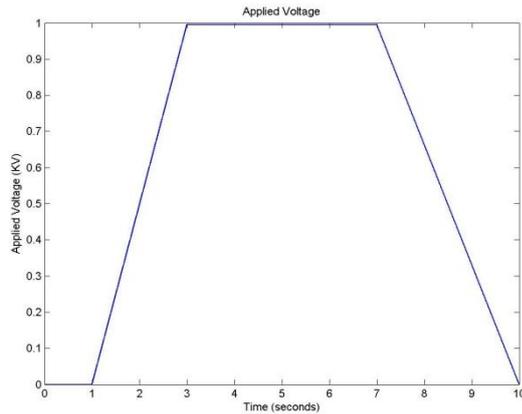


Fig.6 Tractive Effort

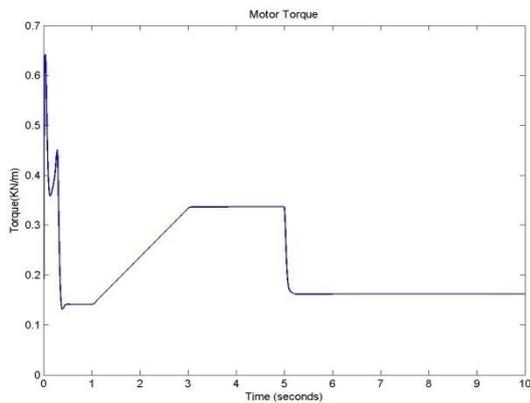


Fig.7 Motor Torque

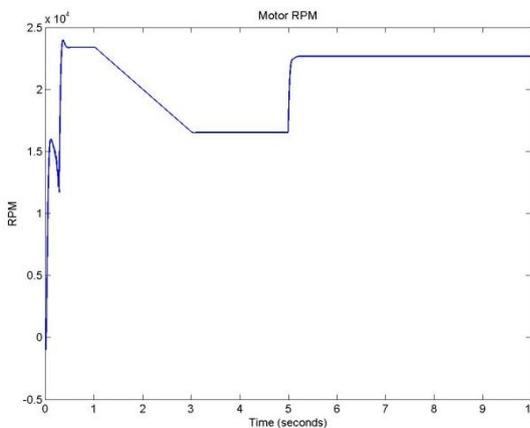


Fig.8 Motor RPM

### C. State Estimation

By tuning the process noise covariance matrix  $Q$ , the performance of the Kalman filters can be studied thoroughly. The determination of the process noise covariance is a more difficult process, so a trial and error approach is applied to find an optimal value at any specific operating point ( $Q=0.001$ ).

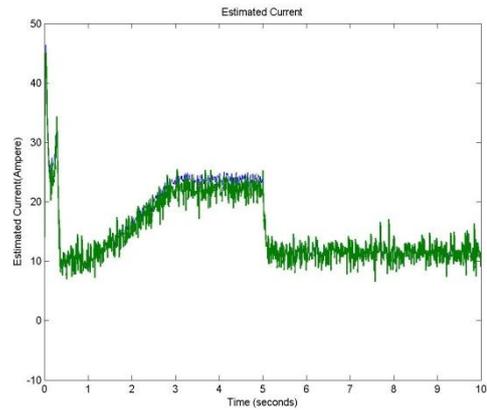


Fig.09: Estimated Current

It can be observed that error for estimated current and real error value are very small approximately negligible, which shows a correctly tuned filter can provide a better estimation for detecting slip using motor parameters.

### VI. CONCLUSION

This proposed idea provides a useful method to measure the slip from motor parameter which is mounted on the wheel set for the locomotion of wheels. Due to reduction of adhesion level, the motor parameters (torque/current) changes by observing change in these parameters of motor, slip is indirectly estimated using Kalman filter. This technique not only provides slip detection but also proves to be a cost effective by avoiding use of extra sensors. Mainly the research deals with technical aspects of slip detection and its estimation, justification of cost effectiveness is only analyzed due to less use of extra sensors compare to other existing techniques. Cost effectiveness of the proposed technique can be proved in future work.

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