Mechanical Systems and Signal Processing 76-77 (2016) 665–676

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Estimators of wheel slip for electric vehicles using torque and encoder measurements

M. Boisvert*, P. Micheau

Université de Sherbrooke and Centre des technologies avancées, Canada

ARTICLE INFO

Article history:
Received 28 August 2015
Accepted 9 February 2016
Available online 8 March 2016

Keywords:
Slip ratio
Observers
Nonlinear model
Electric Vehicles
Mechatronics

ABSTRACT

For the purpose of regenerative braking control in hybrid and electrical vehicles, recent studies have suggested controlling the slip ratio of the electric-powered wheel. A slip tracking controller requires an accurate slip estimation in the overall range of the slip ratio (from 0 to 1), contrary to the conventional slip limiter (ABS) which calls for an accurate slip estimation in the critical slip area, estimated at around 0.15 in several applications. Considering that it is not possible to directly measure the slip ratio of a wheel, the problem is to estimate the latter from available online data. To estimate the slip of a wheel, both wheel speed and vehicle speed must be known. Several studies provide algorithms that allow obtaining a good estimation of vehicle speed. On the other hand, there is no proposed algorithm for the conditioning of the wheel speed measurement. Indeed, the noise included in the wheel speed measurement reduces the accuracy of the slip estimation, a disturbance increasingly significant at low speed and low torque. Herein, two different extended Kalman observers of slip ratio were developed. The first calculates the slip ratio with data provided by an observer of vehicle speed and of propeller wheel speed. The second observer uses an original nonlinear model of the slip ratio as a function of the electric motor. A sinus tracking algorithm is included in the two observers, in order to reject harmonic disturbances of wheel speed measurement. Moreover, mass and road uncertainties can be compensated with a coefficient adapted online by an RLS. The algorithms were implemented and tested with a three-wheel recreational hybrid vehicle. Experimental results show the efficiency of both methods.

1. Introduction

The initial motivation of this study was to develop an efficient regenerative braking for a three-wheel recreational hybrid vehicle electrically powered by its unique rear wheel [1–3]. It is well known that a braking torque applied to a pneumatic tire produces tension on the tire tread such that the tire travels a greater distance than it would if it were free rolling. Such wheel deformation appears as a wheel slip because the wheel angular velocity is different from the vehicle angular velocity [4]. This wheel slip, if not controlled, can lead to loss of adhesion between the braked wheel and the road, hence the risk of vehicle instability. It is therefore imperative to maintain the wheel slip below a threshold (called the critical wheel slip) to ensure efficient braking of the vehicle.

* Correspondence to: 1277 Du Lierre, Sherbrooke, Qc, CA, J1E0K4 819-575-3529.
E-mail addresses: maxime.boisvert@hotmail.ca (M. Boisvert), philippe.micheau@usherbrooke.ca (P. Micheau).

http://dx.doi.org/10.1016/j.ymssp.2016.02.017

Since the 1980s, many electronic systems have been used to ensure the stability of the vehicle by controlling the wheel slip. The most prominent are the anti-lock brake system (ABS), the electronic stability program (ESP), the acceleration slip regulation (ASR) and the vehicle stability control (VSC). However, these systems are usually based on logic switching triggered by wheel acceleration thresholds and not by a continuous slip control algorithm [5].

More recently, for electric and hybrid vehicles (EV, HEV), the driving or braking torque on the powered wheel is directly controlled by an electric motor. This advantage allows the EV and HEV to use the electric torque as the main input on the ABS, ASR and VSC controllers [6,7].

Indeed, a previous study has shown the benefit of precisely controlling the wheel slip during regenerative braking in order to maximize the recovery energy [1]. It thus becomes possible to ensure energy recovery and vehicle stability even in instances of parametric uncertainties such as the inclination of the road, a change in mass or a change in road surface. If a slip controller can allow a higher energy recovery, the first difficulty is not so much in the designing of such a continuous controller to reach the optimal target for wheel slip, but rather to accurately estimate the wheel slip online, particularly when the wheel slip and vehicle speed are low. Indeed, since the definition of slip is a ratio in which the denominator is the speed of the vehicle (in the braking period), the lower the vehicle speed and wheel slip, the more the effect of the disturbances will be significant on the estimated slip. Given the above, results of this study are thus presented at low torque and low speed.

In order to accurately measure vehicle and wheel velocities online, the most convenient method is to process the signals delivered by the encoders located on the powered wheel and on the free rolling wheel. Such encoders are already installed in most current vehicles. However, in our studied vehicle, the speed measurement given by an encoder is corrupted by white noise and a sinusoidal perturbation synchronized with wheel velocity (the frequency of the harmonic disturbance is proportional to the wheel speed). Hence, while many studies consider that velocity measurement is available without other considerations, such information can in actual fact be corrupted. The elimination of such corruptions represents the main goal of this study.

Section 2 presents wheel slip estimators dedicated to electrical vehicles which include the use of corrupted encoder signals. Two different extended Kalman observers of slip ratio are presented. The first is solely based on wheel measurements while the second is based on a nonlinear slip model combining wheel measurements with electrical torque measurements. A recursive least square (RLS) estimator is added to the observer to compensate for uncertainties due to passenger mass or road type [8]. Section 3 presents experimental results obtained on roads with a three-wheel recreational hybrid vehicle which confirm the approach.

2. Two observers

2.1. The considered problem

The problem is illustrated in Fig. 1 when a braking torque (u in N m) is applied to the vehicle. The outputs of this nonlinear system are the linear vehicle velocity v (in m/s) and the wheel velocity w (in m/s) (the angular wheel velocity times the radius of the wheel). The respective measurements of these two outputs, the measured rear and front wheel velocities (v^* and w^* in m/s), are each corrupted with white noise (n_u, n_v) and harmonic noise (d_u, d_v). The latter is delivered by a sinusoid generator function of the vehicle's speed (v). The objective is to combine these data (u, v^*, w^*) with the models in order to estimate the wheel slip ratio online which, during deceleration conditions, is defined as:

$$\lambda = \frac{w - v}{|v|} \tag{1}$$

Hence, the problem is expressed for regenerative braking on hybrid/electric vehicles where the braking torque is well known in real time.

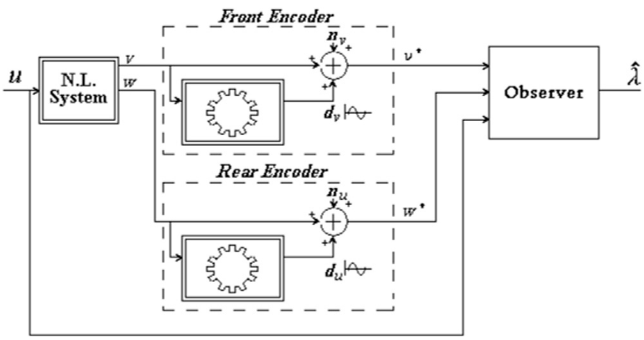

Fig. 1. Problematic of slip observers.