Applied Soft Computing 40 (2016) 70–85

Contents lists available at ScienceDirect

Applied Soft Computing

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

Identification of tire force characteristics using a Hybrid method

R. Talebitooti[a,*], M. Torabi[b]

[a] School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran
[b] School of Automotive Engineering, Iran University of Science and Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 10 August 2015
Accepted 27 September 2015
Available online 19 November 2015

Keywords:
Tire
Magic Formula parameters
Hybrid method
Genetic Algorithm
Levenberg–Marquardt algorithm

ABSTRACT

The present study applies a Hybrid method for identification of unknown parameters in a semi-empirical tire model, the so-called Magic Formula. Firstly, the Hybrid method used a Genetic Algorithm (GA) as a global search methodology with high exploration power. Secondly, the results of the Genetic Algorithm were used as starting values for the Levenberg–Marquardt (LM) algorithm as a gradient-based method with high exploitation power. In this way the beneficial aspects of both methods are simultaneously exploited and their shortcomings are avoided. In order to establish the effectiveness of the proposed method, performance of the Hybrid method has been compared with other methods available in the literature. In addition, the use of GA as a Heuristic method for tire parameters identification has been discussed. Moreover, the extrapolation power of Magic Formula identified with Hybrid method has been properly investigated. Finally, the performance of the Hybrid method has been examined through tire parameter identification with priori known model. The results indicated that the Hybrid method has outstanding benefits such as high convergence speed, high accuracy, and null-sensitivity to the starting values of unknown parameters.

1. Introduction

Performance factors such as ride, handling and fuel efficiency are of significant importance for a vehicle; hence, they need to be considered by vehicle designers. Vehicle handling plays a vital role in vehicle designing, because passenger safety during driving maneuvers is to a large extent dependent on this factor [1]. In fact, the interactions of vehicle and road are through tires; therefore, tire forces and torques determine the vehicle handling behaviors. Nowadays, by using computers, designers have the ability to predict vehicle performance before making a prototype. Such predictions leads to more efficiency in the design activity and lower costs for experimental plans. However, there is a need to develop precise modeling of tire behavior to achieve a good agreement between simulation and experiment.

In this regard, remarkable efforts have been made with both analytical [2,3] and empirical approaches [4–6]. Due to the complexity of the underlying physical phenomenon, an analytical model of a tire based on the physics of the tire construction does not have enough accuracy. Compared to analytical models, empirical models have higher abilities to identify tire behaviors accurately. Empirical models of tire forces are described by a family of curves whose parameters are identified by experimental data [5–7].

A widely used empirical tire model is the so-called Magic Formula (MF) [4]. There have been different versions of this model developed. One of these models known as Delft-tire 96 [5] is commonly used to describe the steady-state tire force and moment characteristics in pure and combined slip conditions; in this present study, it has been used to establish the objective functions. The MF tire model requires a set of parameters to describe the tire dynamic properties. These parameters should be tuned based on the measured data. Several research studies have been conducted in this research line.

Overall, there are two different approaches for parameter identification. The first is off-line parameter identification in which the parameters are determined in experimental laboratory conditions according to certain tire characteristics such as size, constitutive material, inflation pressure, etc. During the car life, however, the operating condition may change because of tire aging (deterioration), inflation pressure, temperature conditions and its side effects on tire behavior. To ensure the accuracy of the model parameters, the corresponding values should be modified and re-estimated with a set of new data. This procedure can be conducted, only by using the tests performed under real conditions on the road. In the second approach called on-line tire identification, off-line parameters value are used (as rough estimations) and then the tire parameters based on the new operating condition will be tuned

---

* Corresponding author. Tel.: +98 21 77240360; fax: +98 21 73021506.
E-mail address: rtalebi@iust.ac.ir (R. Talebitooti).

http://dx.doi.org/10.1016/j.asoc.2015.09.053

again. The methodologies of parameter identifications for these two approaches are absolutely different due to different requirements for solving the associated problems. Accuracy, null-sensitivity to starting values, generalized estimation (non over-fitted values) and in the lower priority, estimation speed, are the requirements for off-line identification of tire parameters. Furthermore, robustness, accuracy and speed of estimation are important requirements for on-line determination of parameters. In this present study, the focus is on off-line identification of MF parameters.

So far, various methods have been presented for the on-line identification. Kiencke and Daiß [8] and Stéphant et al. [9] introduced linear and non-linear observation methods using a bicycle model. Methods on the basis of both time-domain and frequency-domain methodology have been suggested by Sierra et al. [10]. Extended Kalman Filter (EKF) was suggested by Mancosu et al. [11] and Bolzern et al. [12] to determine the tire lateral force on the basis of pre-established results of the theoretical model as well as those obtained from experimental tests on the corresponding real model. In 2009, Kim [1] found that in many other EKF studies conducted to estimate lateral tire forces, tire models with many parameters are included in the vehicle model estimation which can make EKF design more complicated. Furthermore, due to no attention to tire dynamic effects, the models did not provide reasonable results during rapid transient maneuvers. Accordingly, in order to simplify the EKF design, the model was firstly modified into a vehicle with four degrees of freedom. Then, by considering the suspension–tire relaxation length in the model, the transient dynamic behavior was properly estimated.

There are some research studies for off-line identification of tire parameters. Van Oosten and Bakker [13] used a method based on the starting values optimization technique (SVO) to solve the tire identification problem. Since tire identification is highly dimensional and multimodal, a good starting value for the optimization process is an essential constraint. Palkovics and El-Gindy [14] applied the so-called Neuro-Tyre model using an artificial neural network to model tire characteristics. Moreover, Cabrera et al. [15] presented a method called IOA(IMMa[1] Optimization Algorithm) based on a Genetic Algorithm. They claimed that the method outperforms the work done in [13,14] as well as the optimization process done by Nelder and Mead [16]. Oritz et al. [17] presented a summary of the results using the IOA to identify pure and combined tire forces. Later in 2009, they used the IOA presented in [15] with a self-adapting technique (IOA^{sat}). They improved the accuracy of the work while no input variables needed to be chosen by the user [18]. Using only the Genetic Algorithm to reach global minima with good accuracy and speed is not practically possible; therefore, the use of alternative methods is unavoidable. In 2010, Huang Chan and Chen Long used a Genetic Algorithm in order to tune both Pacejka's coefficients of the Magic Formula as well as Neural Network weights. They indicated that Neural Networks can outperform Pacejka tire modeling [19]. Extrapolation capability and time requirements for the optimization process are important factors which should be considered in tire identification methods. However, neither of them were discussed in the comparative study conducted in the available literature presented above.

The present study addresses a Hybrid method to achieve fast and reliable identification of tire model parameters. The proposed method, faced with the optimization problem in parameter identification, indicated a good *exploration* due to the Genetic Algorithm (GA) as the first step and also showed enough power of exploitation as a result of using the Levenberg–Marquardt (LM) algorithm [20,21] as its second procedural step. In addition, as the *Exploration* capability of the method is high; it is not essential to be aware of non-convexity of the searching space or finding good starting values for unknown parameters in the optimization process. In other word, the uniform random numbers in the interval [0, 1] are used as starting values for unknown parameters. Finally, comparing the performance of the present Hybrid method in terms of accuracy and convergence speed with that of other researchers showed the superiority of the proposed Hybrid method.

2. Problem specification

In order to facilitate the precise description of tire forces and moments the SAE[2] [22] has defined the axis system shown in Fig. 1. The X-axis is along the intersection of tire plane and ground with the positive direction forward. The Z-axis is perpendicular to the ground with a positive direction downward. The Y-axis is in the ground plane, makes the axis system orthogonal and right-hand. Tire orientation can be characterized by camber angle γ and side slip angle α. The camber angle is the angle between the wheel plane and the vertical. Side slip angle is the angle between the direction of wheel heading and travel direction. Longitudinal Slip (κ) (sometimes called the slip ratio) may be tentatively defined as the ratio of longitudinal slip velocity and the forward speed of the wheel center [23].

As previously noted, identification of tire forces and moments has been an important issue for designers. Among different approaches, using experimental data to identify a mathematical formula (e.g. Magic Formula [24]) with unknown parameters has attained the most attention. However, estimation of these unknown coefficients from experimental data with good accuracy in a reasonable time has been a challenge. Mathematically the problem can be stated as follows:

$$\min_X S = \sum_i \left[f^{\text{Magic Formula}}(X, C_i) - f^{\text{Measured}}(C_i)\right]^2 \qquad (1)$$

which f represent tire force or moment, C_i is tire operating conditions including vertical force, camber angle, side angle, etc. And X denotes the so-called Magic Formula parameters [24]. In the present work, to tackle this problem, a Hybrid method has been presented.

3. Detailed explanation of the presented Hybrid method

Generally, an algorithm for solving optimization problems is a sequence of computational steps which asymptotically converge to sub-optimal solutions. Numerical optimization algorithms can be classified in two main groups: *Deterministic Algorithms* and *Probability-based* (*Stochastic*) *Algorithms*. A deterministic algorithm will always yield the same output, each time it is given a particular input. However, in a probability-based algorithm randomness is introduced into the search process which might enable the method to escape a local optimum and finally to approach a global optimum. Deterministic algorithms themselves can be roughly categorized into *direct search methods* and *gradient-based methods*. Direct search methods (e.g. Nelder and Mead [16] for linear programming) are also known as derivative-free, or black-box methods. However, Gradient-based methods use first derivatives (gradients) or second derivatives (Hessians) to search landscape. Clearly, proper exploitation of gradient information can significantly enhance the speed of convergence in comparison with a method that does not compute gradients. However, potential weaknesses of gradient-based methods are relative inability to tolerate difficulties such as noisy

---

[1] Área Ingeniería Mecánica Málaga (IMMa) – University of Malaga.

[2] Society of Automotive Engineers.