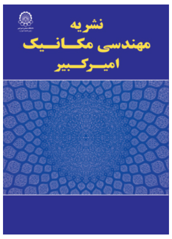

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Identification of Tire Force Model Using Experimental Data of a New Scaled Test Rig for Design of Nonlinear Slip Controller

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ABSTRACT: In this paper, three models for tire friction force are identified using experimental data of scaled test rig. In this setup, a scaled tire is forced to be in contact with a high inertia disk and the friction force between the tire and disk is measured in terms of the slip during braking. For identification of the models, tire's rotational speed, tire's slip and tire's normal force are used as the inputs and the tire's longitudinal force is considered as the output. The experimental data required for identification are collected by force and rotational displacement sensors. By using the measured data, the parameters of tire friction force models are calculated using nonlinear least square method. The identified models are evaluated by data not used in the identification process. The results show that the identified models follow the system outputs with acceptable errors. Among the identified models, the Dugoff model has the better accuracy compared with the Fiala and semi-linear models. As an application, a nonlinear dynamic model of the setup including the identified friction force model is employed to design a nonlinear controller for anti-lock braking system.

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1- Introduction

The behavior of braking system, as a safety system in vehicles, strongly depends on the tire longitudinal force. The tire force is also related to many different parameters such as road friction coefficient, normal force and other characteristics of tire which are dominant in defining the tire force models. The validated tire models are used to simulate the vehicle dynamic behavior in different driving conditions as well as to design the vehicle control systems such as Anti-lock Braking System (ABS).

Among various tire models, Dugoff, Semi-linear, Fiala and Magic tire models are famous because of their unique features. However, the free parameters of these models should be identified for various test rigs. In the following, some researches in the area of model identification for tire force are briefly reviewed: Kong [1] in 2013 identified a Dugoff-based model for scaled tire of a test rig. Guo and Dang [2] in 2008 identified the Uni-model paremeters using a full scale simulator. Cossalter et al. [3] in 2014 identified the transient and steady characteristics of tire force.

In this paper, the parameters of three models are identified for tire force of a scaled test rig using experimental data. Then, the best fitted model is used to design a nonlinear controller for anti-lock braking system based on the test rig model.

2- Identification of Tire Force Model

There are three tire models identified in the present study including Fiala, Semi-linear and Dugoff models. In all these models, the longitudinal tire force is described in terms of the longitudinal slip which is defined as,

$$\lambda = \left(1 - \frac{r\omega}{V}\right) * 100\% = \left(1 - \frac{r_e}{r}\right) \tag{1}$$

where is vehicle speed, r is tire radius, ω is tire rotational speed and r_e is the effective rolling radius of tire.

2- 1- Fiala model

In the Fiala model, the normal pressure distribution on the contact patch is assumed to be parabolic [5]. This model is defined as,

$$f(x) = \begin{cases} C_i \lambda & if \ \ |\lambda| \le \lambda^* \\ sgn(\lambda)\left\{\mu F_z - \dfrac{(\mu F_z)^2}{4C_i|\lambda|}\right\} & if \ \ |\lambda| > \lambda^* \end{cases} \tag{2}$$

where μ and λ^* are defined as,

$$\begin{cases} \mu = \mu_o - \lambda(\mu_o - \mu_s) \\ \lambda^* = \dfrac{\mu F_z}{2C_i} \end{cases} \tag{3}$$

2- 2- Semi-linear model

In this model, the tire longitudinal force is defined as [6],

$$\begin{cases} F_x = \mu(\lambda) F_z \\ \mu(\lambda) = \dfrac{2\mu_p \lambda_p \lambda}{\lambda^2 + \lambda_p^2} \end{cases} \tag{4}$$

2- 3- Dugoff model

In the Dugoff model, a combination of the longitudinal and lateral forces are simultaneously related to both longitudinal and lateral slips [7] as:

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$$F_x = C_i \frac{\lambda}{1-\lambda} f(s) \tag{5}$$

$$F_y = C_\alpha \frac{tan(\alpha)}{1-\lambda} f(s) \tag{6}$$

$$S = \frac{\mu F_z (1-\lambda)\left(1-\varepsilon_r V\sqrt{\lambda^2 + \tan(\alpha)^2}\right)}{2\left[(C_i\lambda)^2 + (C_\alpha tan(\alpha))^2\right]^{\frac{1}{2}}} \tag{7}$$

$$\begin{cases} f(s) = (2-s)s & if \quad s<1 \\ f(s) = 1 & if \quad s>1 \end{cases} \tag{8}$$

3- Test Rig

The test rig including a disc with high inertia and a scaled tire is depicted in Fig.1.

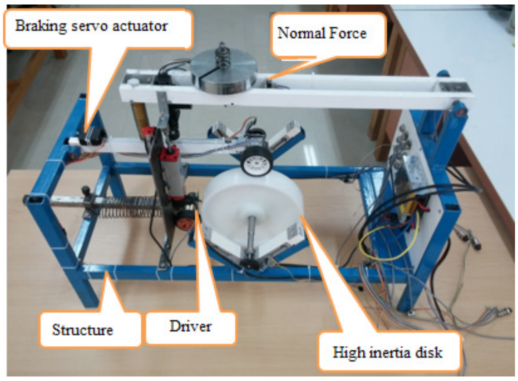

Fig. 1. The test rig

Data logging process is started by driving the disc to reach a specified velocity. Then, the braking is started and the slip along with the longitudinal and normal forces are measured. Identification of parameters is performed by minimizing the following error between test rig and model outputs:

$$min \frac{1}{2}\sum_{k=1}^{N} e_k^2 = min \frac{1}{2}\sum_{k=1}^{N} \left(\left[F_x(k)\right] - \left[\hat{F}_x(k)\right]\right)^2 \tag{9}$$

4- Results and Discussion

The slip vs. time with on/off controller is presented in Fig. 2. Also, the identified longitudinal force based on Dugoff model, for example, is depicted in Fig. 3.

The identified parameters of three models are presented in Tables 1 and 2 also presents the residuals of three models.

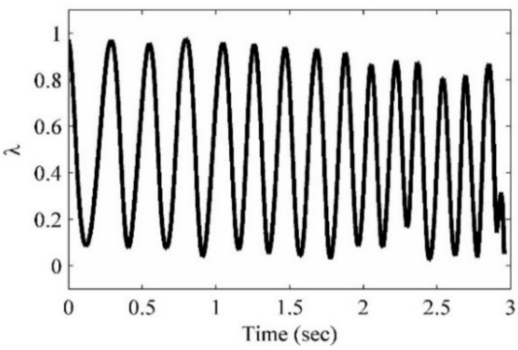

Fig. 2. Longitudinal slip

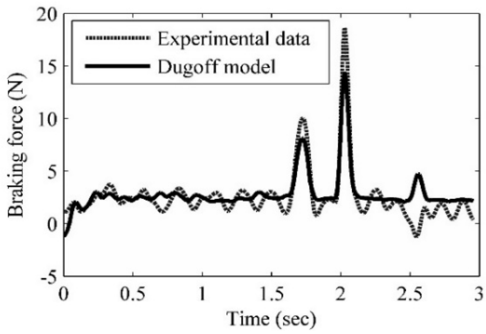

Fig. 3. Dugogg model response

Table 1. Parameters of three models

Dugoff		Semi-linear		Fiala	
C_i	39.4	μ_p	0.127	C_i	19
C_{i0}	800	μ_{p0}	0.2	C_{i0}	600
μ	0.327	λ_p	0.6	μ_o	0.37
μ_0	0.4	λ_{p0}	0.4	μ_{o0}	0.5
ε_r	0.02			μ_s	0.079
ε_{r0}	0.4			μ_{s0}	0.3

Table 2. The residual of three models

Model	Residual
Dugoff	480
Fiala	514
Semi-linear	541

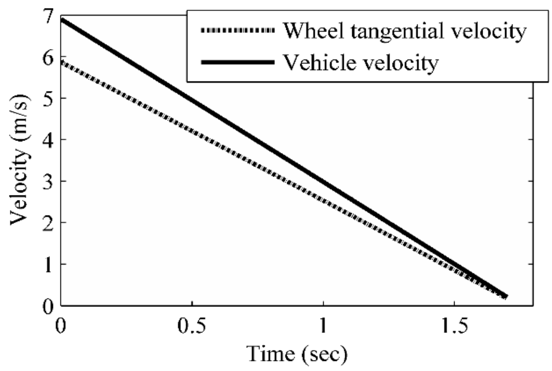

Fig. 4. Vehicle and wheel velocity

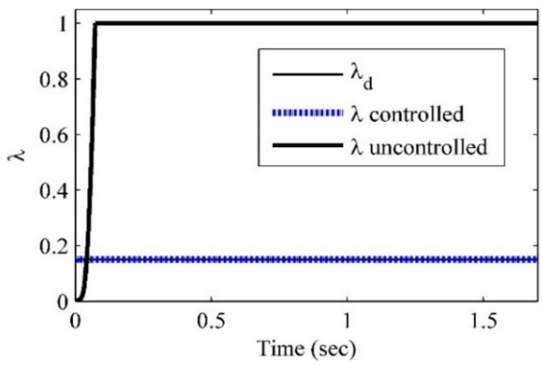

Fig. 5. Longitudinal slip

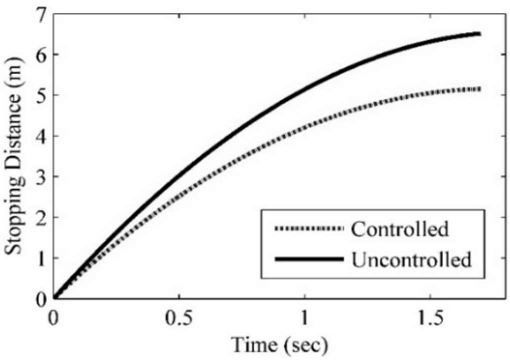

Fig. 6. Stopping distance

5- The Application of Identified Model

Considering the higher accuracy of the identified Dugoff model, this model is employed to design a nonlinear predictive controller for the test rig model to prevent the tire form becoming locked during braking. The details of controller design have been previously introduced by authors research team [8]. The obtained results are depicted in Figs. 4. to 6

6- Conclusions

In this paper, a novel scaled test rig is used to identify the parameters of three tire models including Dugoff, Fiala and Semi-linear models. The parameters of these models are identified by the least square gray box identification method. According to minimum residual criteria, the Dugoff model is found the best identified model compared the others. At the end, a nonlinear controller is designed and simulated for the test rig model including the Dugoff model for tire force.

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