

Application of the Magic Formula Tire Model to Motorcycle Maneuverability Analysis

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ABSTRACT

The Magic Formula Tire Model, recently utilized in maneuverability analysis for automobiles, was applied to a motorcycle simulation model. The correlation between the simulated and measured characteristics for straight running stability and turning performance was compared with those of the current Carpet Plotted Tire Model. Further, the ease of use of the Magic Formula was investigated. The results show that correlation with actual tire characteristics is high for the Magic Formula Tire Model and, further, that the changing of tire properties can be easily accomplished with this model.

1. Introduction

Tire properties are an important determinant of motorcycle maneuverability, and tire models are crucial to behavior simulations employing a mechanical analysis language. The Carpet Plotted Tire Model (CP Tire Model) has traditionally been used as a tire model for expressing properties that include the nonlinear effects of the large camber angle characteristic of motorcycles.

For the CP Tire Model, Linear interpolation methods are used to smoothly express tire properties from discrete measurement data. However, using small increments in interpolation to assure accuracy not only requires processing huge amounts of data, but also makes it difficult to change tire properties.

In this paper, the application of the Magic Formula Tire Model (MF Tire Model) to motorcycles is discussed. Specifically, the correlation between simulation and actual measurement in straight running stability and turning performance, and the efficiency of changing tire properties are discussed.

2. A Tire Model for Motorcycles

Motorcycles have different tire slip angles and camber angles during running than automobiles (Fig.1) ^{(1)~(3)}.

They therefore require a tire model that is capable of assuring accurate representation even with large camber angles.

2.1. The MF Tire Model

Lateral force (F_{y0}) in the motorcycle version of the MF Tire Model, which consists of lateral force and camber thrust, is shown in equation (1) described below. The second term in equation (1) is the equation for camber angle. In equation (1), α represents tire slip angle, γ camber angle, and F_z

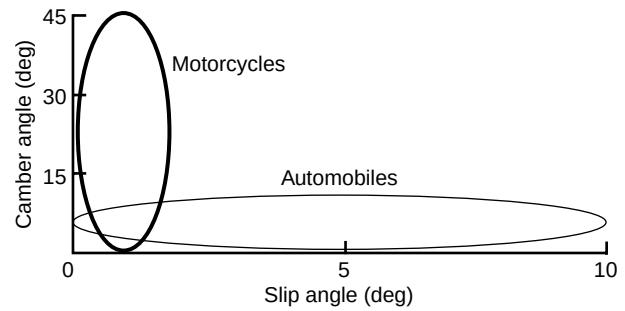


Fig.1 Comparison of motorcycle tires with automobile tires for tire slip angle and camber angle

vertical load. As with the MF equation used for automobiles, the tire model's lateral force F_{y0} is determined by the "MF coefficients" B_y , C_y , D_y , E_y , B_γ , C_γ , E_γ , and Sh_y , and by variables indicating a tire's condition: vertical load, tire slip angle, and camber angle. Values p_0 through p_{17} and γ_0 through γ_9 , which are determined by smoothing measurement data, are termed "MF parameters" and are used to represent differences in tire properties.

$$F_{y0} = D_y \sin[C_y \arctan\{B_y a_y - E_y (B_y a_y - \arctan(B_y a_y))\} + C_\gamma \arctan\{B_\gamma \gamma_y - E_\gamma (B_\gamma \gamma_y - \arctan(B_\gamma \gamma_y))\}] \quad (1)$$

$$\alpha_y = a + S_{hy} \quad (2)$$

$$C_y = p_0 \lambda_0 \quad (3)$$

$$D_y = p_1 \exp(p_2 df_z) (1 - p_3 \gamma_y^2) \lambda_1 F_z \quad (4)$$

$$E_y = \{p_4 + p_5 \gamma_y^2 + (p_6 + p_7 \gamma_y) \operatorname{sgn}(\alpha_y)\} \lambda_2 \quad (5)$$

$$K_y = p_8 F_{z0} \sin[p_9 \arctan\{F_z / (p_{10} + p_{11} \gamma_y^2) F_{z0} \lambda_3\} (1 - p_{12} \gamma_y^2) \lambda_3 \lambda_4] \quad (6)$$

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$$B_y = K_y / (C_y D_y) \quad (7)$$

$$S_{hy} = p_{13} \lambda_5 \quad (8)$$

$$C_g = p_{14} \lambda_6 \quad (9)$$

$$K_\gamma = (p_{15} + p_{16} df_z) F_z \lambda_7 \quad (10)$$

$$E_\gamma = p_{17} \lambda_8 \quad (11)$$

$$B_\gamma = K_\gamma / (C_\gamma D_\gamma) \quad (12)$$

where

F_{z0} : Nominal load

$$df_z = F_z - F'_{z0} / F'_{z0}$$

$$F'_{z0} = F_{z0} l_9$$

Total aligning moment (M_{z0}) is represented by equation (13). Again, the MF coefficients are B_t , C_t , D_t , E_t , B_r , D_r , S_{ht} , and S_{hr} ; the MF parameters are q_0 through q_{25} , γ_{10} , and γ_{11} .

$$M_{z0} = -D_t \cos[C_t \arctan\{B_t \alpha_t - E_t(B_t \alpha_t - \arctan(B_t \alpha_t))\}] \cos(\alpha) F_{y0, (\gamma=0)} + D_r \cos[\arctan(B_r \alpha_r)] \cos(\alpha) \quad (13)$$

$$\alpha_t = \alpha + S_{ht} (S_{ht} = 0) \quad (14)$$

$$\alpha_r = \alpha + S_{hr} \quad (15)$$

$$\gamma_z = \gamma \lambda_{10} \quad (16)$$

$$B_t = (q_0 + q_1 df_z + q_2 df_z^2)(1 + q_3 \gamma_z + q_4 |\gamma_z|) \lambda_4 / \lambda_1 \quad (17)$$

$$C_t = q_5 \quad (18)$$

$$D_t = F_z (q_6 + q_7 df_z)(1 + q_8 |\gamma_z| + q_9 \gamma_z^2) (R_0 / F_{z0}) \lambda_1 \quad (19)$$

$$E_t = (q_{10} + q_{11} df_z + q_{12} df_z^2) \{1 + (q_{13} + q_{14} \gamma_z) (2 / \pi) \arctan(B_t C_t \alpha_t)\} \quad (20)$$

$$B_r = q_{15} \lambda_4 / \lambda_1 \quad (21)$$

$$D_r = F_z (q_{16} + q_{17} df_z + (q_{18} + q_{19} df_z) \gamma_z + (q_{20} + q_{21} df_z) \gamma_z |\gamma_z|) R_0 \lambda_{11} \lambda_1 \quad (22)$$

$$S_{hr} = q_{22} + q_{23} df_z + (q_{24} + q_{25} df_z) \gamma_z \quad (23)$$

where

R_0 : Unloaded tire radius

λ_i : Pneumatic trail

γ_z : Scaled camber angle

2.2. The CP Tire Model

Spline interpolation was performed with the data for tire lateral force and total aligning moment, which were obtained from different combinations of vertical load, tire slip angle, and camber angle using a tire tester. Fig.2 is an example of the resultant spline displayed on a curved surface. Tire slip angle and vertical load were used to calculate, for each camber angle, tire lateral force and total aligning moment

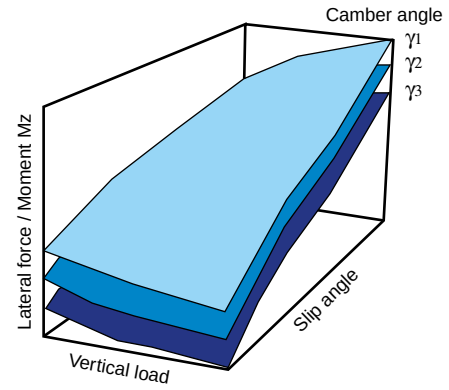


Fig.2 Surface planes of tire properties

on the data surface. In the event that no data surface exists for a corresponding camber angle, the program was designed to perform linear interpolation between the previous and next surfaces.

3. The Simulation Model

The motorcycle model used in the simulation is comprised of eight elements (Fig.3): front tire, rear tire, sprung steering components, unsprung steering components, engine, main body, rider, and rear swing arm. There are nine degrees of freedom of movement: six degrees in the main body, one degree in the steering, and two for the front and rear suspension. The front and rear suspension has nonlinear springs and speed-dependent damping units. The rider is secured to the main body, so only the rider's mass is taken into account. The rigidity of the frame, steering system, and rear swing arm are not taken into account. The running simulation assumes open loop running with no feedback control of the steering system by the rider.

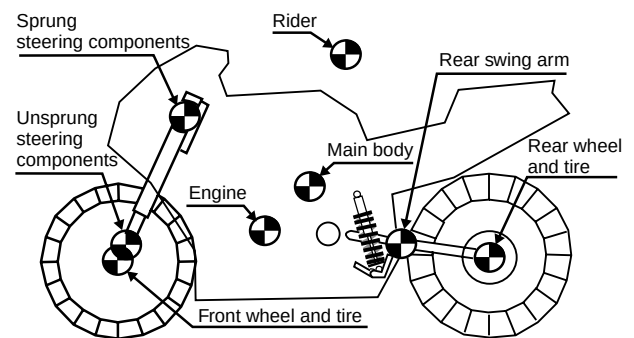


Fig.3 Motorcycle simulation model by multibody analysis language

4. Tire Properties

Tire properties were measured using the flat plank tire tester shown in Fig.4.

The basic data measurement for the tire model used in the simulation was three vertical loads, camber from -5 degrees to 45 degrees; and, tire slip angle, -10 degrees.



Fig.4 Flat plank tire tester

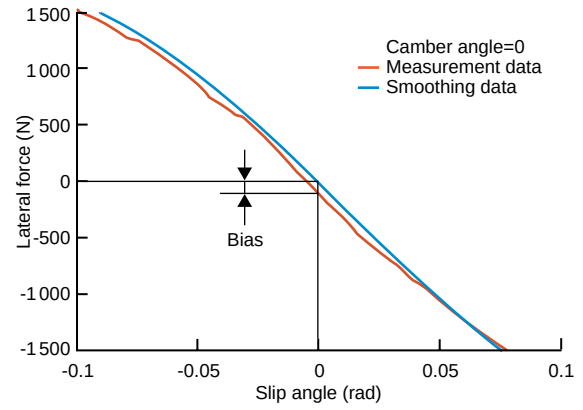


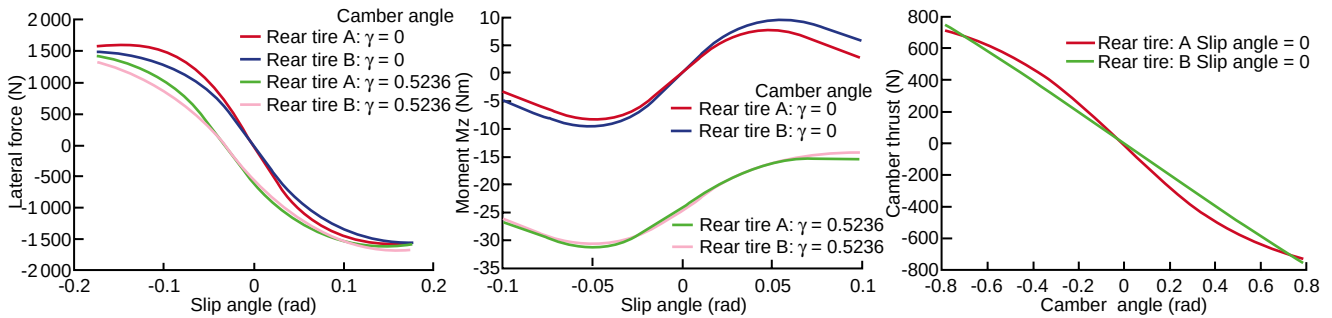
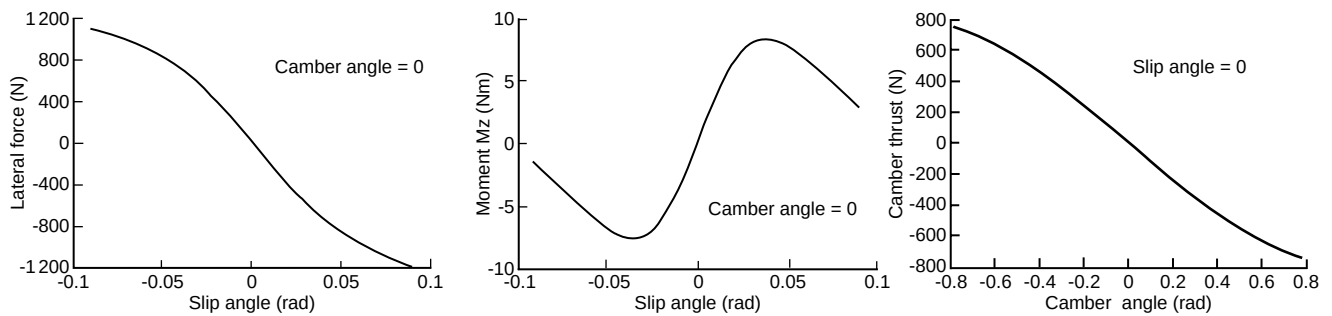
Fig.5 Comparison of tire measurement data before and after smoothing

The results of simulation might differ from prediction when a bias exists in the measurement data.

An example of this would be when tire lateral force or total aligning moment occurs in the straight running state (i.e., camber angle and tire slip angle are both 0 degrees), particularly when operating at lower motorcycle velocities in the simulation. In such cases, this bias is removed in the smoothing stage of the MF Tire Model, wherein the MF parameters are determined. Fig.5 shows measurement data and a post-smoothing curve. The horizontal axis is the tire slip angle; the vertical axis, tire lateral force. This shows that bias in the measurement data is no longer present after smoothing. In the CP Tire Model, measurement data is approximated directly with a spline function.

Then, the difference of properties between two types of

rear tires (A, B) obtained from the measurements is explained. In the graph, tire slip angle is shown on the horizontal axis while tire lateral force and total aligning moment are shown on the vertical axis. The curve representing the lateral force of Tire A has a sharp incline during straight running, i.e., both camber angle and tire slip angle are zero degrees (Fig.6). Near 30 degrees of camber angle there are differences in the absolute value of lateral force. Therefore, Tire A exhibits larger lateral force. During straight running, the curve indicating the total aligning moment of Tire B has a large slope, but there is no significant difference near 30 degrees of camber angle. This shows that the camber thrust stiffness of Tire A is larger than that of Tire B. Fig.7 indicates the front tire's lateral force, total aligning moment, and camber thrust.


 Fig.6 Characteristics of rear tires for lateral force, moment M_z (aligning torque and camber torque), and camber thrust

 Fig.7 Characteristics of front tire for lateral force, moment M_z (aligning torque and camber torque), and camber thrust

5. A Comparison of Running Simulation and an Actual Running Test

5.1. Test Method

Table 1 lists the specifications of the test motorcycle, which was equipped with a steering angle sensor on the steering column; a steering force sensor inside the handlebar pipe, 2-kg (mass) yaw and roll gyro-sensors on the fuel tank, and a 2-kg data recording system on the passenger seat.

A front tire having the properties shown in Fig.7 was used. Two different rear tires, one for each test mode, were used in the straight running stability test. The tire combinations used for this actual running test are shown in Table 2. The body behaviors recorded were steering torque, steering angle, yaw rate and roll angle. A pulsating steering torque was input at 165, 185 and 200 km/h. During the

circular turning test, the rider approached a constant 45m radius at constant velocity. The rider leaned with the motorcycle until steady state turning was achieved. The tire combinations are "Test 2" indicated in Table 2. The range of the test velocities was 40 to 60km/h by 5km/h increments.

5.2. Simulation Results

5.2.1. Straight Running Stability

A comparison between the actual results, the CP Tire Model, and the MF Tire Model has been undertaken under the test conditions of Test 1 and Test 2 illustrated in Table 2. In these tests, yaw rate peak gain relative to steering torque, damping resonance frequency, and yaw rate damping ratio are presented as changes relative to velocity in Figs.8 and 9 respectively.

From Test 1, as velocity is increased, both the CP Tire Model and the MF Tire Model have the tendency of low damping ratio, although there are only slight changes in the damping resonance frequency. This tendency corresponds with the actual measurements.

A comparison between Tire A and Tire B reveals corresponding trends. Tire A shows a higher damping ratio and damping resonance frequency than Tire B having lower lateral force, thereby providing high stability.

The absolute values for yaw rate peak gain relative to steering torque are slightly different from the measured values, but show a corresponding trend.

In the comparison between Tire A to Tire B, it is shown that Tire A with large lateral force capability has a smaller gain than Tire B.

The increase in the lateral force capability of the rear tire generally leads to the higher stability.

Therefore, these results are considered appropriate ⁽²⁾⁽⁴⁾.

Table 1 Test motorcycle specifications

Items	Specifications
Wheelbase (m)	1.401
Caster angle (deg)	23.7
Caster (m)	0.095
Height of center of gravity (m)	0.537
Curb Weight (kg)	204.0

Table 2 Tire specifications for actual running test

	Test 1	Test 2
Front tire	130/70ZR16	130/70ZR16
Rear tire	Tire A: 190/50ZR17	Tire B: 180/55ZR17

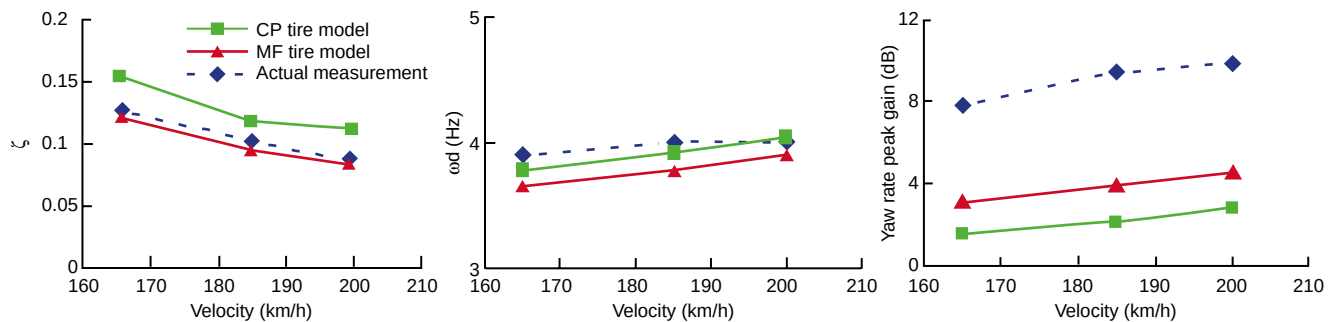


Fig.8 Comparison between simulation and experiment for damping properties in Test 1

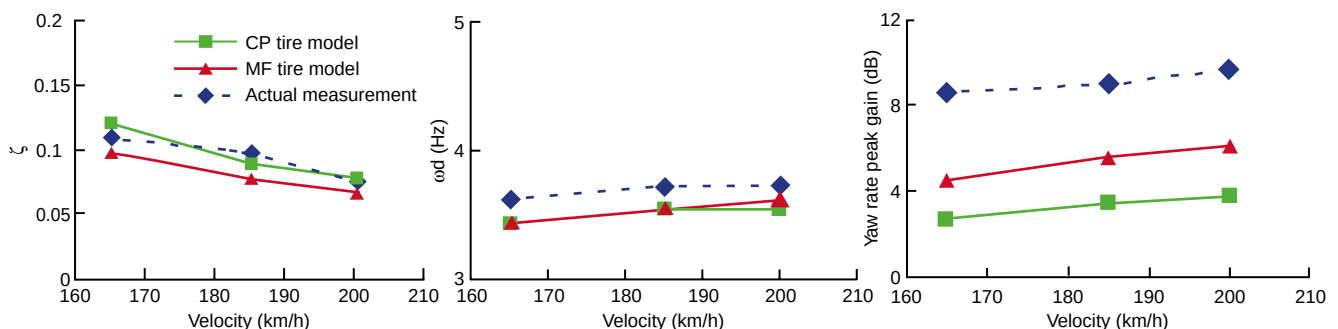


Fig.9 Comparison between simulation and experiment for damping properties in Test 2

The time domain data for steering torque, steering angle, and yaw rate in Fig.10 also indicates that the MF Tire Model is closer to the actual running results than the CP Tire Model.

5.2.2. Turning Performance

Fig.11 shows time domain data for steering torque, steering angle, yaw rate, and roll angle obtained in a circular turning simulation performed with the CP Tire Model and the MF Tire Model. Lateral acceleration was 0.5 G. The tendency and absolute values of steering angle, yaw rate, and roll angle indicated by both tire models correspond to the actual measurements. The steering torque and steering angle relative to lateral acceleration are shown in Fig.12. The tendency and absolute values of steering angle closely correspond to the actual measurement. Hence, the CP and MF Tire Models closely predict the actual measurements.

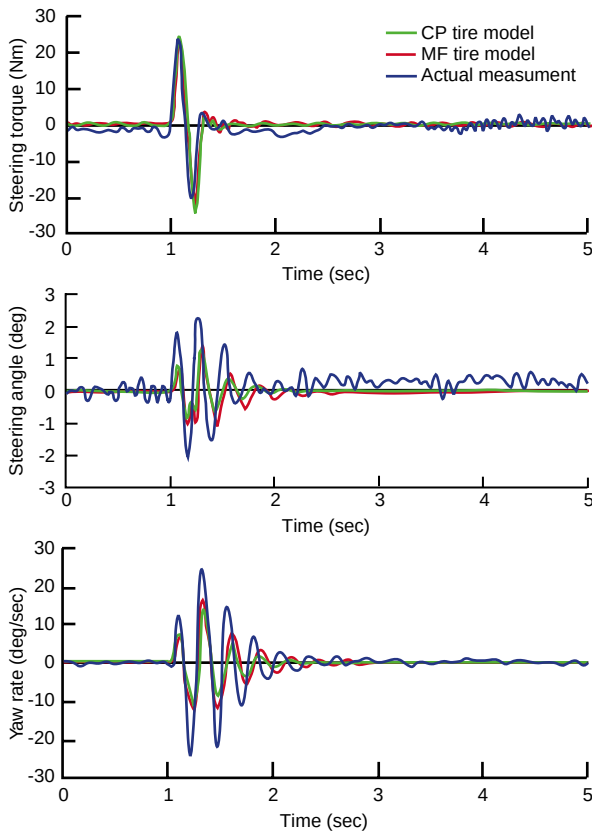


Fig.10 Comparison between simulation and experimental steering torque, steering angle and yaw rate

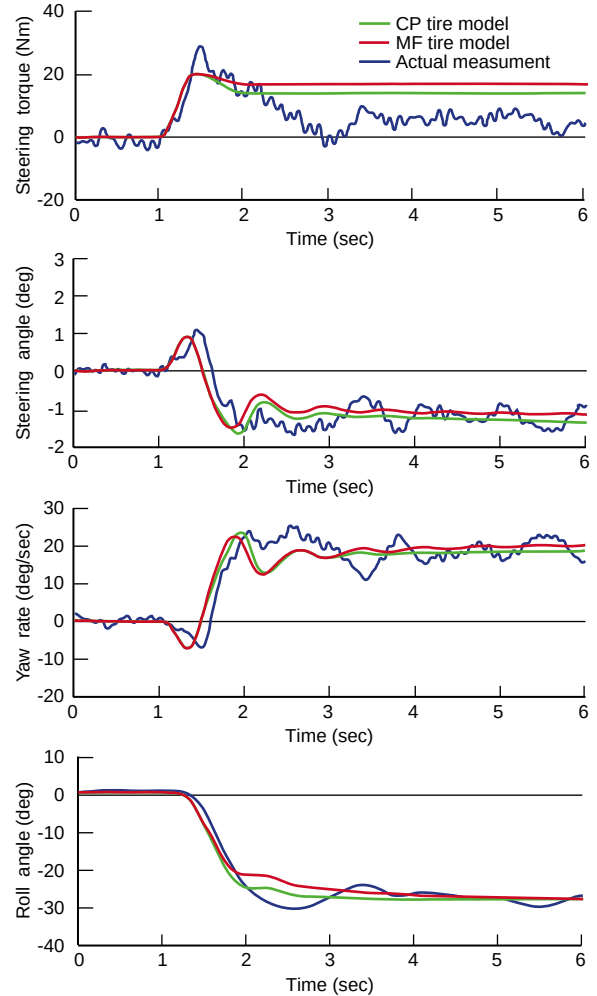


Fig.11 Comparison between simulation and experimental steering torque, steering angle, yaw rate and roll angle

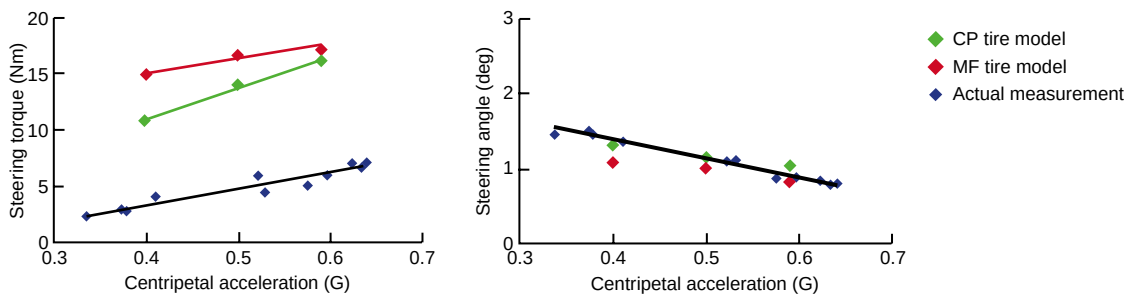


Fig.12 Comparison between simulation and experimental steady state turn

There is, however, a significant difference in steering torque properties. This is most likely due to the fact that the simulation model assumed open loop control, with no feedback control of the steering system. It is also necessary to consider a rider model that accounts for steering operations and individual differences among riders and so forth.

As for the applicability of the CP and the MF Tire Models to motorcycle simulation models, it takes almost the same period of time to convert the same amount of tire measurement data into the individual data format. However, looking at the ease of analysis, the MF Tire Model is more efficient in tire changes and parametric studies.

6. Conclusion

Motorcycle simulations performed with the CP Tire Model and the MF Tire Model verified the correlation of these models with actual measurements, and confirmed the following.

- (1) With respect to straight running stability, the MF Tire Model shows better correlation with actual measurements in comparison with the CP Tire Model.
- (2) With respect to turning performance, the MF Tire Model shows roughly the same correlation with the actual measurements as the CP Tire Model.
- (3) The MF Tire Model based on the tire measurement data, which is applied to the Motorcycle Simulation Model, facilitates changes in tire properties better in comparison with the CP Tire Model. In order to improve the accuracy of motorcycle simulation, it is necessary to adopt frame rigidity and the dynamic properties of the rider in the simulation model.

Furthermore, it is also required to develop a tool that is capable of calculating tire properties and expediting parameter studies.

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