

Friction Estimation at Tire-Ground Contact

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ABSTRACT

The friction estimation at the tire-ground contact is crucial for the active safety of vehicles. Friction estimation is a key problem of vehicle dynamics and the ultimate solution is still unknown. However the proposed approach, based on a simple idea and on a simple hardware, provides an actual solution.

The idea is to compare the tire characteristic at a given friction (nominal characteristic) with the actual characteristic that the tire has while running. The comparison among these two characteristics (the nominal one and the actual one) gives the desired friction coefficient. The friction coefficient is expressed in vector form and a number of running parameters are identified. The mentioned comparison is an efficient but complex algorithm based on a mathematical formulation of the tire characteristic. The actual tire characteristic is somehow measured in real time by a relatively simple smart wheel which is able to detect the three forces and the three moments acting at the hub.

A Gough-plot is derived to map the measured lateral tire force and self-aligning moment to a unique estimate of the lateral friction coefficient. Extending the Gough-plot by the (measured) longitudinal tire force due to longitudinal slip from braking or accelerating, makes the estimation method more robust. A look-up table is computed offline and allows for instantaneous friction estimation. The longitudinal friction coefficient is estimated in a similar way, making explicitly use of the longitudinal slip. Alternatively, measured tire forces and moments can be used for robust longitudinal slip estimation as well.

Both the theoretical and experimental issues are presented in the paper.

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1. INTRODUCTION

A number of highly qualified papers that address the estimation of the friction at tire-ground interface can be found in the literature. Over the past ten years of research, the focus remains on the following topics [1]:

1. Enhancement of the active safety of vehicles and reduction of road accidents
2. Driver warning the available friction
3. Broadcasting of the road surface friction condition (info for vehicle drivers or traffic info centers)

4. Enhanced road maintenance
5. Traffic management

A comprehensive research is reported in [1] where a number of different technologies are compared referring to friction estimation.

Basically there are four different strategies for friction estimation, which are based on

1. physical vehicle models
2. force measurement
3. vision
4. data fusion

A comprehensive overview of the literature produced on road friction estimation is out of the scope of this paper. We cite a limited number of recent papers belonging to the four addressed groups.

1. Physical vehicle models [1,5,17] are prone to the uncertain vehicle parameters and cannot detect properly friction at each single wheel. Nonetheless they can provide some enhancement with respect to the normal situation in which the driver uses mainly his/her inspection (of the road surface) and steering wheel torque as the (fuzzy) data to estimate friction.
2. Force measurement [1,2,3,4,16] seems a very promising way of detecting tire-road friction, provided that the sensors and the procedures are robust and signal to noise ratio is sufficiently low. Our paper belongs to this group of research and aims to overcome the addressed problems.
3. Vision can be a very effective way of estimating friction [1] but some additional efforts for reducing costs seems necessary. One major vision is estimating the friction that the wheel experiences earlier. This is quite important.
4. Mixing all the information available could be a viable (and cheap) way to estimate friction, however the accuracy strongly depends on which and how information is used, (see e.g. [6,7]).

The paper deals with a brief description of the smart wheel that has been used to measure the forces at tire-ground interface. Then the maneuvers providing the forces and moments at the rear wheel of a reference vehicle are reported. Finally, the algorithm used to detect the friction potential is presented and applied.

2. SMART WHEEL

The concept design of the developed smart wheel for measuring forces and moments is shown in Fig. 1 ([8, 9, 10, 11, 12, 13, 14]). The three spoke structure, supporting the central part of the wheel, is constrained at the rim by means of three sliding spherical joints. Such a structure is statically determined and so it is quite easy to find the forces acting at the hub if the forces acting at the spoke tips (i.e. at the constraints) are measured. Due to the nature of the constraints (sliding spherical joints) only two forces in two orthogonal directions are acting at each spoke tip, so the force measurement is simple. The proof that the three spoke structure is statically determined is shown in Fig. 1. Actually Fig. 1 shows that the two constraints at two adjacent cantilevers/spokes (e.g. joints 1, 3) are equivalent to the virtual rotational joint (1+3). So the three spoke structure is equivalent to a simply supported beam, the simplest statically determined structure.

The joints must be frictionless and so they have been designed as laminas located between each spoke tip and the rim (Fig. 2). The shape of the laminas has been optimized in order to reproduce a sliding spherical joint, i.e. a joint with very high axial and tangential stiffness and with very low radial stiffness (the addressed directions

are given referring to the wheel). Additionally, the lamina allows rotations around the tangential direction and the axial direction. The rotation around the spoke axis is provided by a proper compliant cross shape of the spoke. Finally, to eliminate friction a quasi-statically determined structure is obtained, since the tip of each spoke is connected to the rim by means of an elastic joint (joints 1, 2, 3 in Fig. 1).

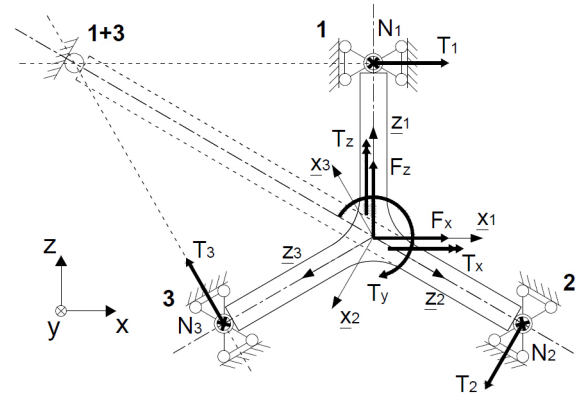


Figure 1. Concept design of the smart wheel.

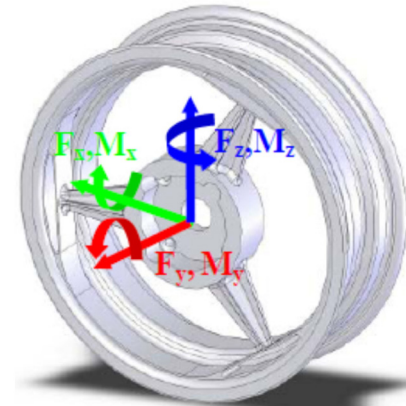


Figure 2. Actual structure of the smart wheel. The three sliding spherical joints at the three spoke tips are realized by means of three laminas.

The three spoke structure can be instrumented by means of 12 strain gauges at the positions shown in Fig. 3 and connected in half-bridge configuration. Their positions have been defined in order to maximize the output (voltage) of the strain gauges for all combinations of loads applied at the wheel center. The strain gauges resistance is 350 Ω , sufficiently high to reduce the power consumption. The strain gauges are intentionally located in the area where the bending moments acting at each spoke produce high strains. In Fig. 4 the measuring wheel mounted on the reference car is shown. The performance of the smart wheel is reported in Tab 1.

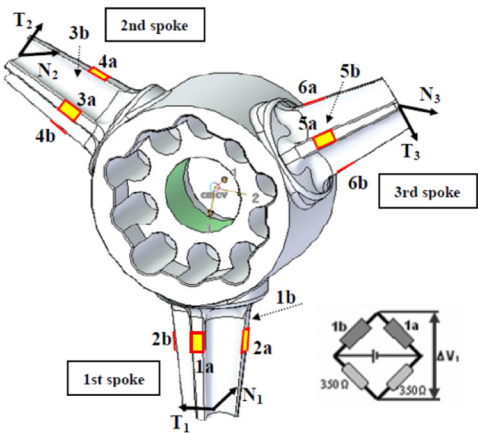


Figure 3. Location of the 12 strain gauges.

Table 1. Measuring wheel technical specifications.

Maximum force	F_x, F_y, F_z	15	kN
Uncertainty 95%		0.5	% F.S.
Resolution		± 1	N
Maximum torque	M_x, M_y, M_z	3.5	kNm
Uncertainty 95%		0.3	% F.S.
Resolution		± 0.2	Nm
Cross-talk		$< \pm 2.0$	%
Acquisition frequency		200	Hz

3. TEST MANEUVERS

A reference vehicle has been taken into consideration for simulating the running of actual vehicles along public roads. A series of manoeuvres have been performed on (dry or wet) asphalt surface at the Politecnico di Milano referring to the vehicle in Fig. 4, whose data are reported in Tab 2.



Figure 4. Smart wheel and the reference car used for friction estimation.

Table 2. Measuring wheel specifications.

Mass	1300	kg
Wheel base	2.552	m
Centre of gravity distance from front axle	1.05	m
Track	1.56	m
Tire radius	0.313	m
Yaw moment of inertia	2050	kgm ²
Tire	205/60 R15	

The manoeuvres are

- steering ramp at approximately 30 km/h
- straight running, applying parking brake ramp from approximately 30 km/h
- steering ramp (spiral) plus parking brake ramp from approximately 30 km/h

The first two manoeuvres have been conceived to test the estimation algorithm in condition of pure lateral or longitudinal slips, respectively. The third manoeuvre is proposed to test the algorithm efficiency in case of combined longitudinal and lateral slip.

In Fig. 5, 6, 7 the longitudinal and lateral forces and the self-aligning torque on the measuring wheel are reported for the considered manoeuvres.

The contact forces of the rear right tire are considered and reported in the following figures.