

# Race Motorcycle Smart Wheel

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## ABSTRACT

A wheel able to measure the generalized forces at the hub of a race motorcycle has been developed and used. The wheel has a very limited mass. It is made from magnesium with a special structure to sense the forces and provide the required level of stiffness. The wheel has been tested both indoor for preliminary approval and on the track.

The three forces and the three moments acting at the hub can be measured with a resolution of 1N and 0.3Nm respectively.

A specifically programmed DSP (Digital Signal Processor) embedded in the sensor allows real-time acquisition and processing of the six signals of forces/torques components.

The signals are sent via Bluetooth to an onboard receiver connected to the vehicle CAN (Controller Area Network) bus. Each signal is sampled at 200Hz.

The wheel can be used to derive the actual tyre characteristics or to record the loads acting at the hub.

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## INTRODUCTION

The knowledge of the force acting at the tyre-road interface is of crucial importance for the optimal setup of race motorcycles.

In case of motorcycles, there is a very wide variety of driving situations, load conditions and driving styles to be considered. Numerical simulations can provide a rough idea of the possible maximum loads on the wheels but a large amount of uncertainty still remains [1].

In this paper, the real time measurement of the force at the tyre-road interface by an innovative measuring wheel is considered. The wheel [2, 3, 4, 5, 6] able to measure the forces and moments at tyre-road interface is designed to be fitted at the front of a race motorcycle to be used to measure the forces while driving on a race track. An accurate knowledge of the force transmitted by the tyres will allow the designers to optimize the suspension settings and to improve the design of the wheel itself.

The measure of the forces and moments at the interface between the tire and road has been widely discussed in the literature and many applications can be found referring to devices developed for such measurements ([7,8]). The sensing unit of such measuring systems can be realized by means of strain gauges ([9,10,12]) or piezo-resistive sensors [11]. Different measuring hubs are present on the

market [1,2,3,4,5,6], [9,10,11,12]). Most of them are characterized by complex hardware and the ones developed for motorcycles [9] are difficult to apply to race motorcycles due to their excessive mass.

This paper is focused on the development of a new measuring wheel, similar to the ones presented in [2,25]. The design of this smart wheel has been realized on the basis of the patented [14,15] system described in [16,17]. The resulting measuring wheel is ideally a statically determined three spoke structure connecting the hub to the rim of the wheel. The three spoke structure is connected to the rim by means of specially designed (and patented) sliding spherical joints ([18,19]). The stiffness of the joints make the structure quasi-statically determined. The deformation of the three spoke structure is measured by means of strain gauges and related to the actual forces and moments acting between the tire and the road.

The first section of the paper describes the models (analytical and FE) used during the development of motorcycle measuring wheel. The mechanical design is presented in the second section of the paper. The electronic hardware is described in section 4. Finally the calibration of the sensor and the some experimental test data are reported.

## MEASURING WHEEL MODELLING

The concept design of the developed smart wheel for measuring forces and moments is shown in Fig. 1 ([2,3,4,5,6], [16,17], [25]).

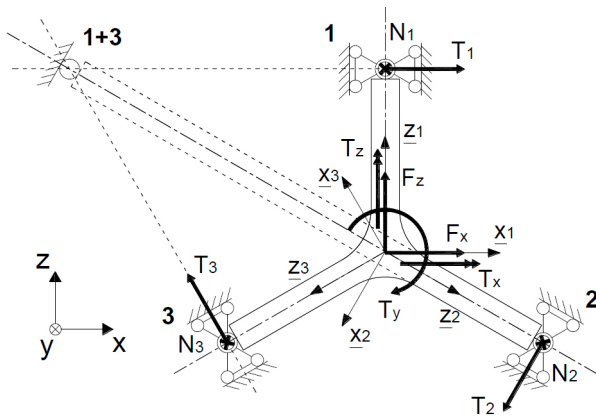


Fig. 1. Concept design of the smart wheel.

The three spoke structure is constrained to the rim by means of three joints positioned at the tip of each spoke. The joints are plates located between each spoke tip and the rim (see Fig. 2). Their shape has been optimized in order to reproduce a joint with very low axial and rotational stiffness. The final aim is to obtain a quasi-statically determined structure by constraining the tip of each spoke to the rim by means of translating spherical joints (1, 2, 3 in Fig. 1). Fig. 1 shows that the two constraints at two adjacent cantilevers/spokes (e.g. 1, 3) are equivalent to the virtual rotational joint (1+3).

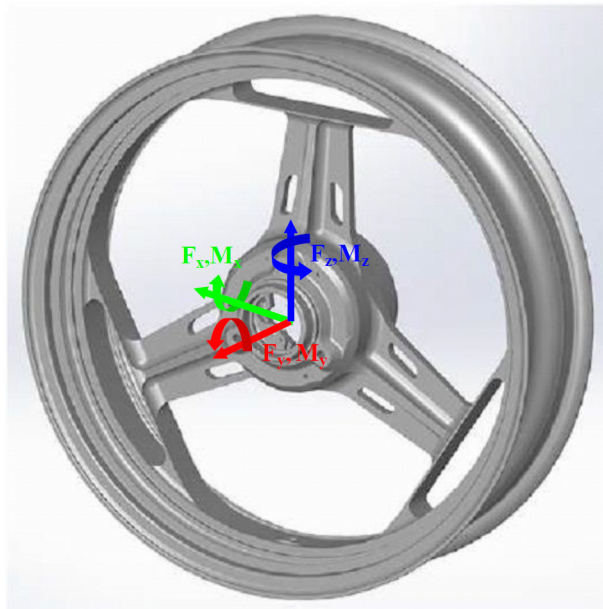


Figure 2. Measuring wheel structural model. The global coordinate system is highlighted.

With this type of structure, each spoke tip is subject to two forces only, so that a total of 6 forces are acting at the three spoke tips. Namely, there are the three forces  $T_1$   $T_2$   $T_3$  and other three forces  $N_1$   $N_2$   $N_3$  normal to them. The six forces  $T_i$   $N_i$  at the spoke tips can be measured by sensing the strain level due to the bending moments at each spoke root. Given such six forces, the three forces and the three moments at the centre of the sensor  $F$  can be computed by solving simple equilibrium equations.

The solid model of the smart wheel is shown in Fig. 2.

The three cantilever/spoke structures are 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 centre. The strain gauges resistance is 350  $\Omega$ , sufficiently high to limit the wheel power requirement.

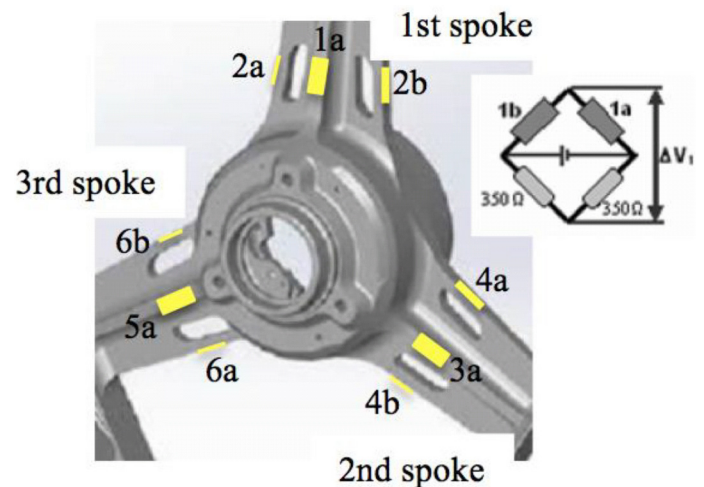


Figure 3. Location of the 12 strain gauges.

The strain gauges are intentionally located in the area where the bending moments acting at each cantilever/spoke produce high strains.

The theoretical calibration matrix has been derived to compute the vector of the forces and moments acting on the sensor given the strain gauge measures.

On the basis of the simple model which considers the smart wheel as a statically determined structure (Fig. 1), a more refined analytical model describing the wheel as a quasi-statically determined structure, (i.e. statically undetermined structure) has been derived taking into account the compliance of the elastic sliding spherical joints (see [16]).

A set of six stiffness has been introduced in order to model each joint at the spoke tip (axial ' $k_a$ ', radial ' $k_{rx} - k_{ry}$ ', torsional ' $k_t$ ' and bending ' $k_{bt} - k_b$ ' stiffness) and a central rigid ring has been considered for taking into account the very stiff central part of the smart wheel (Fig. 4).

A central rigid ring has been included to model the wheel hub. The structure with the central rigid ring can be considered equivalent to a structure in which the three spokes are connected at the centre and each spoke is divided into two parts. The first part of the spoke, from the tip to the connection with the rigid ring, is considered as a deformable beam. The second part of the spoke, from the centre of the structure to the external part of the rigid ring, is considered as a rigid beam, see Fig. 5. The spokes have been modelled as tapered beams.

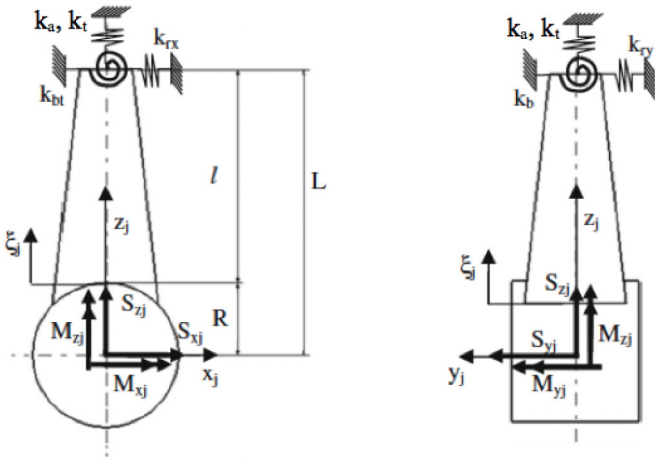


Figure 4. Single spoke representation of the statically undetermined structure with a central rigid ring.

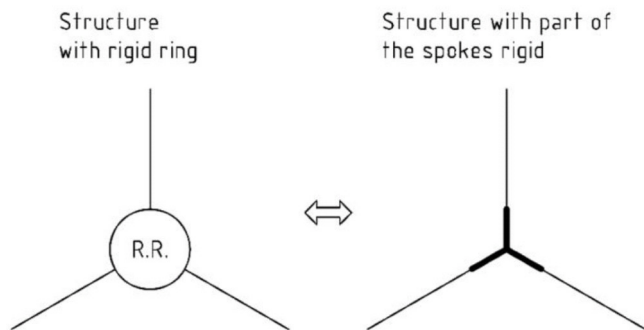


Figure 5. Wheel structure with a central rigid ring. Bold line: rigid partitions of the spokes.

The analytical expressions of the equations system which allows to estimate the output differential voltages  $\Delta V_j$  at the Wheatstone bridges as a function of the system parameters (joint stiffness, three spoke structure geometry, strain gauges characteristic,...) and of the vector  $\mathbf{F}$  of the forces and of the moments acting at the smart wheel are reported in [16]. A discussion on the theoretical performances and error propagation of this type of sensors is reported in [17].

By defining the vector of the forces and of the moments acting at the centre of the wheel (see the coordinate system in Fig. 1) as

$$\mathbf{F} = [F_x \ F_y \ F_z \ T_x \ T_y \ T_z]^T$$

and the vector of the strains measured at the locations shown in Fig. 2

$$\mathbf{E}_s = [\varepsilon_{1a} \ \varepsilon_{1b} \ \varepsilon_{2a} \ \varepsilon_{2b} \ \varepsilon_{3a} \ \varepsilon_{3b} \ \varepsilon_{4a} \ \varepsilon_{4b} \ \varepsilon_{5a} \ \varepsilon_{5b} \ \varepsilon_{6a} \ \varepsilon_{6b}]^T$$

The following relationship holds

$$\mathbf{F} = \mathbf{F}(\mathbf{E}_s) \quad (1)$$

The above equation becomes

$$\mathbf{F} = \mathbf{C} \cdot \mathbf{E}_s \quad (2)$$

if a linear relationship between  $\mathbf{F}$  and  $\mathbf{E}_s$  holds.

A suitable connection (half bridge) of the strain gauges allows the measurement of two bending moments. Therefore the vector of the bending strains signals reduces to  $\mathbf{E}_b = [\varepsilon_1 \ \varepsilon_2 \ \varepsilon_3 \ \varepsilon_4 \ \varepsilon_5 \ \varepsilon_6]^T$ .

The relationship between  $\mathbf{F}$  and  $\mathbf{E}_b$  becomes

$$\mathbf{F} = \mathbf{C}_b \cdot \mathbf{E}_b \quad (3)$$

where  $\mathbf{C}_b$  is a  $6 \times 6$  constant square matrix referred as sensor calibration matrix.

The relationship between the vector of the bridges output voltages  $\Delta \mathbf{V}$  and the vector  $\mathbf{F}$  is the theoretical calibration matrix  $\mathbf{M}_{st}$

$$\mathbf{F} = \mathbf{M}_{st} \cdot \Delta \mathbf{V} \quad (4)$$

## MECHANICAL DESIGN

The measuring wheel has to be designed in order to have mass and stiffness properties similar to those of the standard racing wheel while providing a good sensitivity [6].

The design of the measuring wheel has been performed in three stages

1. Preliminary design, definition of the geometrical dimensions of the spokes and of the joint stiffness by means of the analytical model previously described
2. Joints design, design of the connecting plates in order to get the desired joint stiffness by using a finite element code
3. Detail design of the full wheel

In the first phase the most important parameters of the measuring wheel (material, spoke length, cross section and tapering) are selected in order to meet the prescribed values of mass and stiffness and to obtain a high level of deformation at the strain gauges locations.

A magnesium alloy with a good combination of mechanical properties and corrosion resistance has been selected.

Additionally, target values for the stiffness of the joint have been set in order to have a structure close to a statically determined one (i.e. axial and rotational joints stiffness have to be small with respect to the radial joint stiffness). In fact, as explained in [17,25], the strain level read by the strain gauges drop if the structure becomes statically undetermined, i.e. axial and rotational stiffness of the joints are above a critical value depending on the geometry of the measuring wheel.

A multi-objective optimization approach has been applied [20,22,27] in the first design stage. The system has been optimised by considering two loading conditions: for both manoeuvres, a static