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Motorcycle smart wheels for monitoring purposes

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Abstract

Smart wheels able to measure the generalized forces at the hub of a motorcycle have been developed and used. The wheels have a very limited mass. They are forged and milled to obtain a special patented structure, able to accurately sense the generalized forces and to provide the required level of stiffness. The wheels have been tested both indoor (for preliminary approval according to internal standards) and on the track. The three forces and the three moments at the hub can be measured with a resolution of 0.5 N and 0.1 Nm. The real-time computation of the forces/torques components is performed by a DSP board programmed to apply the calibration and rotation matrix. The signals are sent via Bluetooth to an onboard receiver connected to the vehicle CAN bus. Each signal is low pass filtered and sampled at 200Hz.

1 Introduction

The knowledge of tyre/terrain contact forces is a crucial task for the design and operation of road vehicles.

In the literature a large number of sensors have been proposed to measure forces and moments on passenger cars [9, 13, 14, 11, 12], and some of them are already available on the market [15, 25, 8, 7, 22, 17]. However, referring to motorcycle wheels, applications of such kind of sensors are still to be widespread and no examples except the one presented by Gobbi et. al. [10] can be found in the literature.

An alternative to such sensors is based on the use of *virtual sensors*, i.e. instead of a direct measure of the physical quantities of interest, a reasonable estimation is obtained by means of model-based observers that rely on simple dynamic models [2]. In particular, with reference to motorcycle tyres lateral forces, attempts have been done in [24, 26]. In [24] motorcycle tyre forces are estimated by means of a sliding mode observer. The observer is based on a simple 4 d.o.f. motorcycle model describing lateral, roll and yaw motion of the motorcycle along with the steering fork dynamics. A similar approach is followed in [26], where an Extended Kalman Filter (EKF) architecture has been adopted to estimate the relevant states related to motorcycle tyres contact forces.

The use of virtual sensors, although very attractive thanks to the reduced cost, comes with a certain amount of approximation, mainly related to the vehicle numerical model and to the tyre model adopted. Especially regarding motorcycles, there is a very wide variety of driving situations, load conditions and riding styles to be considered and therefore a large amount of uncertainty still remains.

In this paper, the real time measurement of the forces and moments at the tyre-road interface by innovative measuring motorcycle wheels is described. The developed wheel, denoted as *Smart Wheel*, has been conceived and realized with the aim to maintain comparable performances with respect to conventional motorcycle wheels, thus limiting their influence on the motorcycle behaviour itself. Both front and rear wheels for high performance motorcycles have been realized, made from forged magnesium alloy, with a special structural layout of the sensing element designed for optimizing the sensor accuracy. The six forces and moments acting at the centre of the wheel are reconstructed from the strain measures at specific locations of the wheel structure. Real time data processing and transmission is performed by a specifically developed Digital Signal Processor (DSP). Signals are sent via Bluetooth to an onboard receiver connected to the motorcycle Controlled Area Network (CAN-bus).

In the first section of this paper, the design and realization process of the Smart Wheel is briefly summarised, recalling the main technical features and specifications of the sensor. The reader is addressed to [10] for a more comprehensive description of the sensor.

In the second section, some possible applications of the Smart Wheel are presented and described.

2 Smart Wheel Design

The core design of the Smart Wheel is based on the three-spoked statically determined scheme of Figure 1.

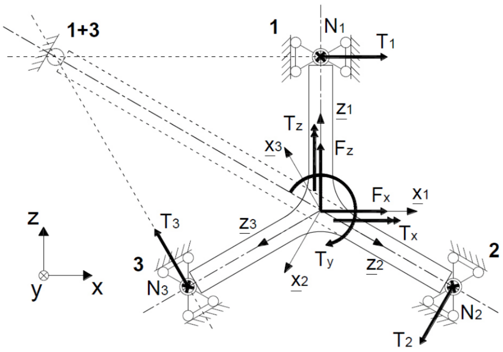

Figure 1. Smart Wheel conceptual scheme.

The three-spoked structure of Figure 1 is the sensing element of the Smart Wheel, and is constrained to the wheel rim by means of three joints located at each spoke tip. With this scheme, knowing the six forces acting at the spoke tip ($T_1, T_2, T_3, N_1, N_2, N_3$), the three forces and moments acting at the centre of the structure can be calculated. Forces T_i and N_i acting at the spoke tips can be obtained by measuring the strain induced by the bending moments acting on each spoke.

Such a scheme has been successfully applied also for the design of innovative six-axis load cells for general applications [5, 19, 6].

2.1 Smart Wheel structural design

The model of the Smart Wheel is shown in Figure 2 (left). The wheel is instrumented with a set of 12 resistive strain gauges to measure the bending strain acting on each plane of the spokes. The strain gauges are connected in a half Wheatstone bridge configuration as shown in Figure 2 (right).

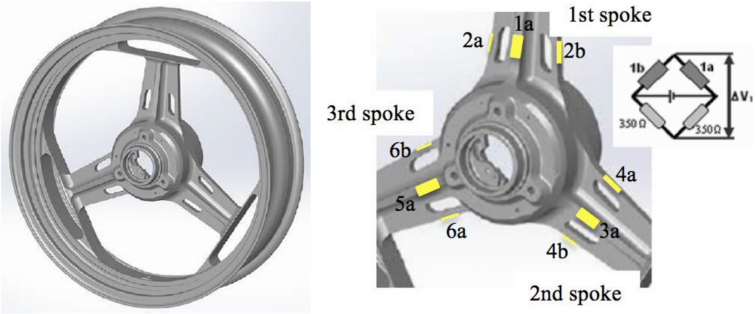

Figure 2. Solid model of the Smart Wheel (left) and detail of strain gauges location and connection (right).

The geometry of the three spokes has been optimised to enhance the measurement accuracy: tapered spokes have been adopted to ensure a uniform strain field at the strain gauges location, making the sensor more robust to the (small) errors in strain gauges positioning. To increase the strain level measured by the strain gauges, elliptical holes have been realised near the strain gauge locations as shown in Figure 2.

The connection between the three spokes and the wheel rim has been realised by means of lamina-like joints. The stiffness of these joints is crucial for the measuring performances of the Smart Wheel. In fact, the presence of the joint slightly modifies the statically determined structural scheme of Figure 1 into the statically undetermined one of Figure 3.

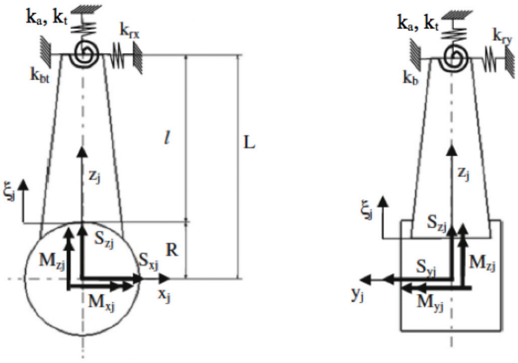

Figure 3. Statically undetermined structural scheme of the sensor (only one spoke is shown). The stiffness of the joints at the spoke tips have been introduced through axial and torsional equivalent springs.

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

$$\mathbf{F} = [F_x, F_y, F_z, T_x, T_y, T_z] \tag{1}$$

and the vector $\mathbf{E_b}$ of the bending strains measured at each of the six half Wheatstone bridges

$$\mathbf{E_b} = [\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4, \epsilon_5, \epsilon_6] \tag{2}$$

a linear relation between $\mathbf{F}$ and $\mathbf{E_b}$ holds:

$$\mathbf{F} = \mathbf{C_b E_b} \tag{3}$$

where $\mathbf{C_b}$ is a 6x6 matrix. From the linear relation between the bending strain and the output voltages of the Wheatstone bridges, the vector of input forces $\mathbf{F}$ of Equation 3 can be related to the vector of the six Wheatstone bridges output voltages $\mathbf{\Delta V}$ as

$$\mathbf{F} = \mathbf{M_{tst} \Delta V} \tag{4}$$

where $\mathbf{M_{tst}}$ is a 6x6 matrix denoted as *Calibration Matrix*. This matrix is obtained by means of a proper calibration process of the sensor [10].

Numerical analysis have been conducted to assess the structural performances of the Smart Wheel, both in terms of structural stiffness and durability requirements. To increase the wheel radial stiffness and make it more uniform over a complete wheel revolution, four magnesium discs have been press-fitted and glued to the wheel rim as shown in Figure 4.

Figure 4. Detail of the magnesium discs added to increase the wheel radial stiffness and its uniformity over a wheel complete revolution.

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2.2 Signal acquisition board

An integrated DSP board provides real time data acquisition and transmission. As the wheel rotates, the measured forces are function of the wheel absolute revolution angle. The wheel angular position is measured by an absolute encoder located inside the wheel hub; by combining the data from the strain gauges and the wheel revolution angle, the forces in the motorcycle reference system can be calculated. The computed forces and moments are then sent to the motorcycle CAN-bus, each signal is sampled at a frequency of 200 Hz. The block diagram of the DSP board is shown in Figure 5

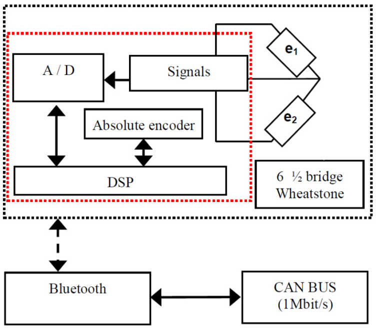

Figure 5. DSP board hardware block diagram.

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3 Smart Wheel possible applications

This section aims at providing an overview of some possible applications of the developed motorcycle Smart Wheels.

3.1 Friction potential evaluation

The maximum force attainable at the tyre/road interface is limited by the tyre characteristics and by the road surface conditions [21]. The possibility to monitor and, even, have a certain prediction of the tyre/road frictional conditions is a very discussed topic in the scientific literature since it opens broad perspectives in terms of vehicle active safety improvements [3, 16], road accident reductions [27] and even safety improvement of autonomous vehicles [23, 18].

If on one hand friction potential estimation is a broadly discussed topic in the field of vehicle engineering [20, 1, 4], actually no applications can be enumerated in the field of motorcycles. The innovative tyre force sensor presented in this paper could be employed to improve the active safety of motorcycles.

Forces and moments measured by the Smart Wheel could be integrated with a model-based estimator of the tyre states as shown in Figure 6.

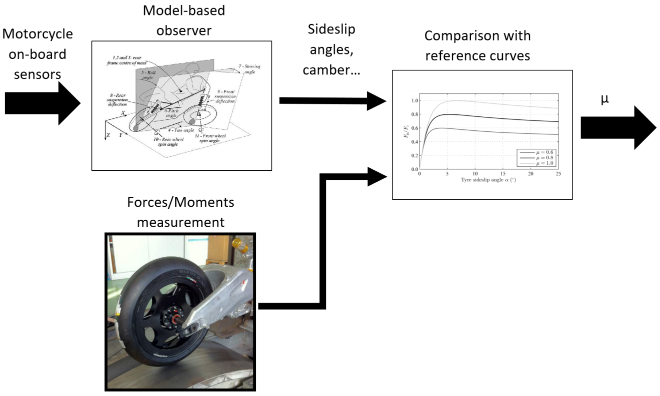

Figure 6. Block diagram of a possible implementation of a friction potential estimation algorithm based on model-based observer and Smart Wheel data acquisitions.

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The tyre state estimator receives as input data measured by on-board motorcycle sensors [24] and computes the required tyre states such as sideslip and camber angles. Having the forces measured by the Smart Wheel and the observed tyre states, the actual tyre characteristic can be derived. The tyre/road friction potential can now be identified by a direct comparison between the computed tyre curves and reference ones.

3.2 Motorcycle tyres characterisation

After calibration, the measuring wheel is tested while running at high speed on the Ruotavia test-rig at Politecnico di Milano (see Fig. 7). It is evident the very good agreement between the forces acquired by the measuring wheel and signals from the test rig that is used for dynamic validation purposes.

The measuring wheel can be used for motorcycles tyres characterization both indoor and outdoor.

3.3 Fatigue load spectra definition

In road vehicle design, wheels play a primary role in terms of safety and are subject to severe indoor tests before the production stage. Structural safety and durability are the most important concerns of wheel designers, for this reason, every new model of wheel has to pass many tests before obtaining production approval. Conversely, lightweight design has increased its importance in recent years and nowadays is a main driver in the design of vehicle wheels. Obviously the aim at mass minimization comes with a contextual reduction of safety coefficients and this means that, in the design stage, more accurate and refined numerical models need to be implemented and a deep knowledge and awareness of in-service loads is required.

The presented Smart Wheel could be useful for measuring actual in-service loads acting on the motorcycle. The knowledge of input load spectra allows for lightweight design by maintaining the required

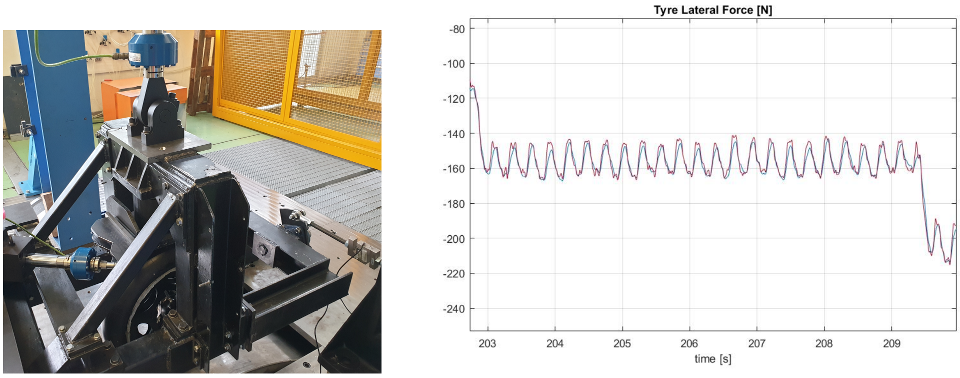

Figure 7. Smart wheel experimental validation on the Ruotavia Test Rig (on the left). Lateral force at constant speed (on the right). Smart wheel signal in red, Test Rig signal in blue.

level of structural safety and durability.

Experimental testing on a high performance motorcycle have been conducted on a race track. The motorcycle was equipped with two Smart Wheels for measuring tyre contact forces at front and rear, roll angle and velocity sensors. Data related to ten consecutive laps of the circuit have been acquired, for an overall mileage of 40 km. During the tests, several different loading conditions have been identified, namely

- Pure longitudinal motion
- Pure cornering
- Cornering with longitudinal force
- Passage over a curb
- Gear shift

For each of the identified loading conditions, fatigue load spectra have been derived by means of a rainflow counting method.

Figure 8 shows an example of a measured load spectrum of the vertical force acting at the rear wheel during pure longitudinal loading conditions (motorcycle acceleration phase).

4 Conclusions

In the paper an innovative Smart Wheel able to measure tyre forces and moments of high performance motorcycles has been presented. The wheel is based on a quasi-statically determined three-spoked structure, the three forces and moments acting at the central hub are calculated by monitoring the bending strain level at each of the three spokes. The real-time calculation of the forces/torques components is performed by a DSP programmed to apply the calibration matrix and the rotation matrix. Acquired data are sent to a bluetooth receiver connected to the motorcycle CAN bus.

The proposed smart wheel can be used in conjunction with proper controls to enhance motorcycle stability. Some applications in which the use of Smart Wheels could provide sound improvements to the current state of the art are presented in the paper and summarised hereafter.

- Accurate monitoring of the road surface can be obtained for ITS applications referring to local friction detection for safe ride. Data collected by smart wheels can be broadcasted to local transportation authorities to inform riders on the status of the road pavement.

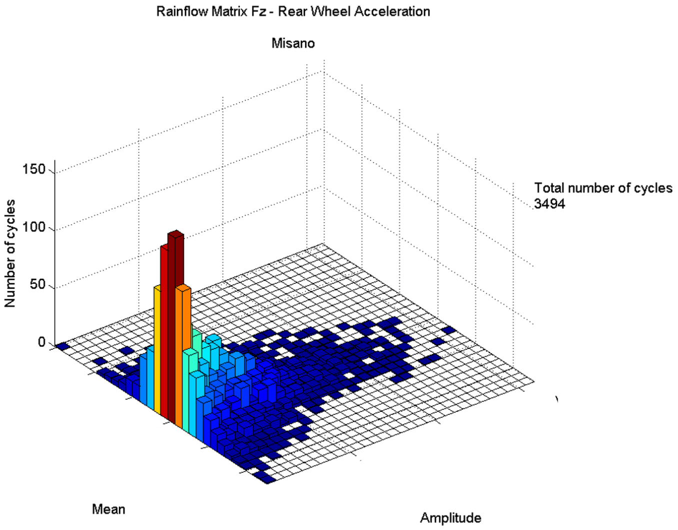

Figure 8. Motorcycle acquired load spectra of the vertical load at the rear wheel during a pure longitudinal loading condition.

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- The use of Smart Wheel allows an efficient and accurate characterization of motorcycle tyres.
- The wheels can be used to monitor the loads acting at the hub, which allows two main advantages. Firstly this provides the designers with a more detailed and accurate awareness of the actual in-service loads of the components, allowing lightweight construction. Secondly, by employing smart wheels, the damage level of most weak (and light) components can be continuously updated. When the safety limit is reached the component has to be substituted.

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