

6-Axis Measuring Wheels for Trucks or Heavy Vehicles

Massimiliano Gobbi, Giampiero Mastinu, Giorgio Previati, and Mario Pennati
Politecnico di Milano (Tech Univ)

ABSTRACT

The measurement of the contact forces between road and tires is of fundamental importance while designing road vehicles.

In this paper, the design and the employment of measuring wheels for trucks and heavy vehicles is presented. The measuring wheels have been optimized in order to obtain high stiffness and the approximately the same mass of the wheels normally employed.

The proposed multicomponent measuring wheels are high- accuracy instruments for measuring the dynamic loads during handling and durability testing. The measuring wheels can replace the wheels of the truck under normal operation. Such family of wheels plays a major role in modern road vehicles development.

The measuring wheel concept design is based on a patented three-spoke structure connected to the wheel rim. The spokes are instrumented by means of strain gauges and the measuring wheel is able to measure the three forces and the three moments acting at the interface between the tire and the road. It uses an inboard digital system for wireless data transmission.

The main objective of the design process undertaken was improving the measuring wheel sensitivity and its accuracy while limiting the mass complying with stiffness and stress constraints.

The simple design, the good performance, in terms of accuracy, dynamic behaviour, limited mass and low cost represent the main features of the system.

The truck measuring wheel is currently in use to determine actual loading spectra useful for estimating the life rims and suspension components. A truck running on mixed routes (highway, city, ...) with different drivers and the force data are acquired via the measuring wheel and directly processed on line.

CITATION: Gobbi, M., Mastinu, G., Previati, G., and Pennati, M., "6-Axis Measuring Wheels for Trucks or Heavy Vehicles," *SAE Int. J. Commer. Veh.* 7(1):2014, doi:10.4271/2014-01-0816.

INTRODUCTION

The knowledge of the force acting at the tyre-road interface is of crucial importance for the design of the vehicle suspension. Tyre-road forces can be estimated by simulating the vehicle when performing different manoeuvres in different load conditions. In this case, tyre behaviour, road roughness and all vehicle data (geometry, inertia parameters, transmission, ...) should be known in the most possible accurate way. In case of trucks, and heavy vehicles in general, there is a very wide variety of driving situations, load conditions and driving styles. In this situation, numerical simulations can give a rough idea of the possible maximum loads on the wheels but a large amount of uncertainty still remains.

In this paper, the real time measurement of the force at the tyre-road interface is considered. An innovative measuring wheel [1, 2, 3, 4, 5] able to measure the forces and moments at tyre-road interface is designed to be fitted on a truck in substitution to a standard wheel hub in order to be used to measure the forces during the truck driving with different drivers, thus exploring all the possible driving and load conditions. An accurate knowledge of the force transmitted by the tyres will allow the designers to optimize the design of the wheel rim and of the suspension components. This knowledge will also be useful for tyres designer to avoid fatigue induced failures in tyres such as belt separation [6].

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 hubs 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], [9, 10, 11, 12]). Most of them are characterized by complex hardware, often realized by using special (and costly) materials in order to improve the stiffness and reduce the weight of the wheel.

This paper is focused on the development of a new measuring wheel, similar to the ones presented in [1, 2, 3, 4, 5]. The design of this smart wheel has been realized on the basis of the patented [13], [14] six axis load cell described in [15], [16]. 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 ([17], [18]). 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.

1. MEASURING WHEEL CONCEPT DESIGN

The concept design of the developed smart wheel for measuring forces and moments is shown in Fig. 1 ([1, 2, 3, 4, 5], [15], [16]).

The three spoke structure is constrained to the rim by means of three special joints positioned at the tip of each spoke. The joints are actually especially designed plates located between each spoke tip and the rim. Their shape has been optimized in order to reproduce a joint with very low axial and rotational stiffness and high radial 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 this type of joint (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).

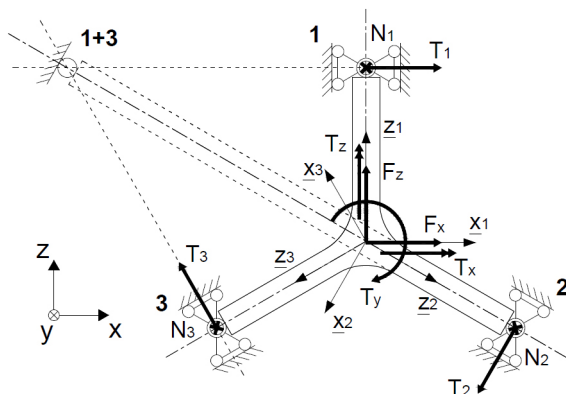


Fig. 1. Concept design of the smart wheel.

With this type of structure, each spoke tip is subject to two forces only, so that a total 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 deformations 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 load cell F can be computed by solving simple equilibrium equations.

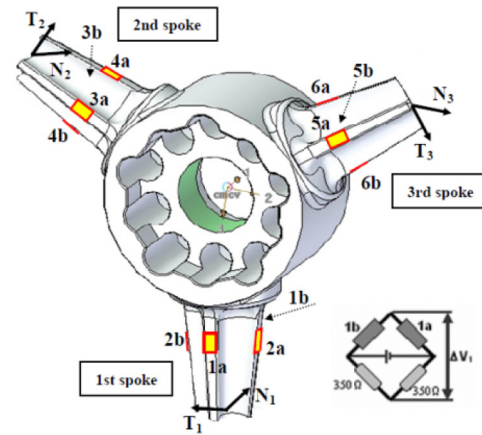


Fig. 2. Location of the 12 strain gauges.

The three cantilever/spoke structure can be instrumented by means of 12 strain gauges at the positions shown in Fig. 2 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 Ω , sufficiently high to limit the power requirement.

The strain gauges are intentionally located in the area where the bending moments acting at each cantilever/spoke produce high strains. The solid model of the smart wheel is shown in Fig3.

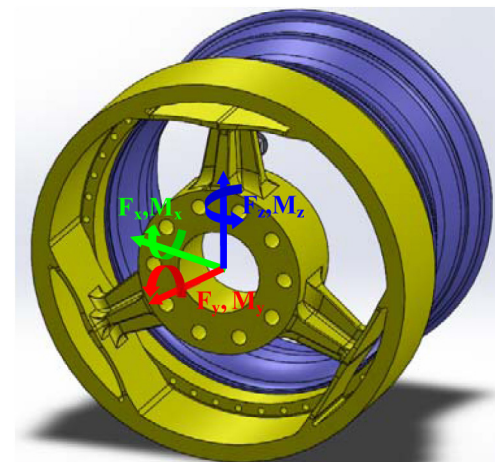


Fig. 3. Measuring wheel model. The global coordinate system is highlighted.

Three mechanical models of the smart wheel have been implemented in order to accurately predict the performances of the sensor. 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. Starting from a simple model which considers the smart wheel as a statically determined structure (shown in Fig. 1), a more refined analytical model referring to the quasi-statically determined structure, (i.e. statically undetermined structure) has been derived taking into account the compliance of the elastic sliding spherical joints (see [15]) and the central part of the three spoke structure described as a central rigid body.

By defining the vector of the forces and of the moments acting at the centre 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.

As stated in the previous section, 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 6×6 constant square matrix referred as sensor calibration matrix. By considering the ideal statically determined structure (Fig. 1), the vector $\mathbf{E}_b$ is directly related to the vector of the 6 forces $\mathbf{T} = [N_1 \ T_1 \ N_2 \ T_2 \ N_3 \ T_3]^T$ at the three joints. By inverting eq. 2, the vector of the 3 forces and 3 moments $\mathbf{F}$ can be derived. It is possible to define the relationship between the vector of the bridges output voltages $\Delta \mathbf{V}$ and the vector $\mathbf{F}$ by means of the theoretical calibration matrix $\mathbf{M}_{\text{tst}}$

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

In order to accurately quantify the smart wheel calibration matrix and to design the joints at the tip of each spoke, a more complex analytical statically undetermined model of the sensor has been derived (see [15] for further details). 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).

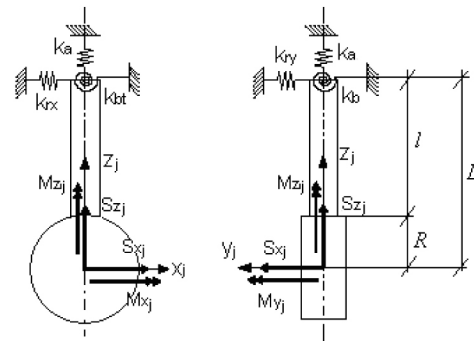


Fig. 4. Single spoke representation of the statically undetermined structure with a central rigid ring.

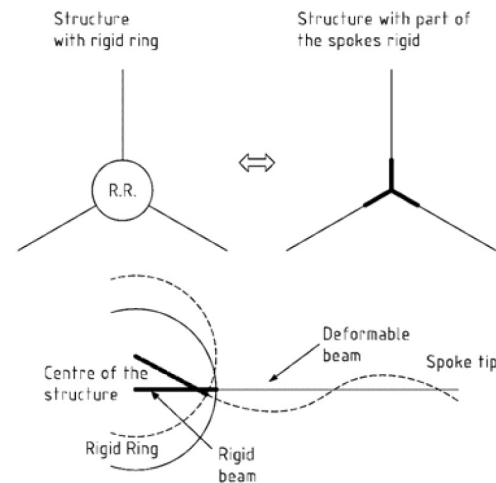


Fig. 5. Single spoke representation of the statically undetermined structure with a central rigid ring. Bold line: rigid partitions of the spokes. Continuous line: non-deformed structure. Dotted line: qualitative deformation of a spoke.

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. This situation is shown in the upper part of Fig. 5. In the lower part of Fig. 5 the deformation of each spoke is shown. The rigid part of the spoke undergoes a rigid rotation and translation.