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Engineering evaluation of "reactivity" of racing bicycle wheels

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Abstract

During road cycling the cyclists can evaluate the behavior of a wheelset in terms of several performance requirements: among all, the wheels reactivity, defined as the wheels quickness in transforming cyclist actions into bicycle acceleration, resulted to be one of the main performance requirements perceived by the cyclists. Together with the subjective evaluation test sessions, a set of engineering indexes, representing the most representative technical measurements of the cyclists perceived performance requirements, is also needed for an effective product innovation approach. Aim of the present work was the development of a method for the computation of a wheel reactivity engineering index. The method is based on the computation of the energy absorbed by the wheel during a sprint action performed by the cyclist. Each energy contribution to the total energy absorbed by the wheel was quantified; the parameters considered for the index computation were obtained by the analysis of data collected in the field tests of an instrumented bicycle. The high correlation coefficient obtained between the engineering reactivity index calculated for three different wheels and the perceived reactivity evaluated by the cyclists, regarding the same wheels, was considered as a validation of the developed method.

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1. Introduction

Structural and inertial properties of bicycle wheels strongly influence the dynamics of the bicycle. In a previous study [1], the authors focused on the collection of the cyclist quality requirements by means of a structured method based on observational analysis as well as on personal and group interviews: the result was that cyclists evaluate the wheelset behavior considering a set of 6 performance requirements: Reactivity, Handling, Road Holding, Comfort, Forward Rolling Efficiency, Stability to Crosswind. The results of the subjective evaluation tests performed during that study (Giubilato *et al.* 2013) showed that high differences between the different tested wheelsets were perceived by the testers among all the performance requirements. This suggested the development of engineering complex indexes which could represent a technical measurement of the cyclist perceived performance requirements. The wheels reactivity is one of the main performance requirements evaluated by the cyclists during road cycling: it is defined as *the wheels quickness in transforming cyclist actions into bicycle acceleration*. Previous works were focused on the study of the wheels structural behavior (Giubilato and Petrone 2011), comfort properties (Petrone and Giubilato 2011, Giubilato and Petrone 2012) and on the measurement of the wheel loads (Drouet and Champuox 2010). To authors knowledge, there are no studies regarding the development of engineering complex indexes which express the user evaluation about the sport equipment under test. Aim of the present work was the development of a method for the engineering computation of the wheels "reactivity" as perceived by the cyclists. The reactivity of a bicycle wheel depends on its physical characteristics (mass, inertia and stiffness) and their influence is counted with a scientific approach based essentially on the computation of the energy absorbed by the wheel during a chosen action.

2. Method

2.1. Approach

The reactivity was assumed to be correlated with the energy absorbed by the wheels during a sprint. In fact, during a sprint with rider standing on the pedals, the motion of each wheel is the sum of four contributions:

- x: translation in the direction of the bicycle motion;
- θ: rotation around the wheel axis;
- φ: rolling rotation around the axis which links the points of contacts of the two wheels with the road surface;
- δ: rotation around the steering axis (only for front wheels).

The speed variation of each wheel motion component involves a contribution to the increment of the kinetic energy absorbed by the wheel. The rotation δ of the front wheel around the steering axis was neglected because of the low value reached by the steering angle during a sprint. In addition to these, the elastic energy due to the wheel deformation has to be considered. The total energy E^- absorbed by a wheel during a sprint is the sum of the kinetic and deformation energies. The lower total energy absorbed by a wheelset, corresponds to the faster response of the wheelset to the cyclist action: this is assumed to mean higher reactivity. The different contributions to the total energy absorbed by a wheel during a sprint are showed in details below.

2.2. Energy absorbed by a wheel during a sprint

- **Translational kinetic energy increment**

The wheel can be modeled as a body of mass m (fig. 1.a) subjected to a translational motion with speed v. The bicycle acceleration involves an increase of the wheel translational speed Δv, $\Delta E_{K\ transl}$ is the relative kinetic energy increment (1).

$$\Delta E_{K,transl} = \frac{1}{2} \cdot m \cdot \Delta v^2 \tag{1}$$

- **Rotational kinetic energy increment**

The bicycle acceleration involves an increase of the wheel rotational velocity Δω (fig. 1.b), $\Delta E_{K,rot}$ is the relative kinetic energy increment:

$$\Delta E_{K,rot} = \frac{1}{2} \cdot I_P \cdot \Delta\omega \tag{2}$$

I_P = polar moment of inertia of the wheel [kg · m^2]

- **Tilting kinetic energy**

$$\Delta E_{K,tilt,i} = \frac{1}{2} \cdot \left(\frac{I_P}{2} + m \cdot r_W^2 \right) \cdot \left(2 \cdot \pi \cdot f_\varphi \cdot \varphi_0 \right)^2 \tag{3}$$

φ_0 = maximum roll angle of the bicycle reached during the sprint [rad]
f_φ = wheel roll motion frequency [Hz]
r_W = wheel radius [m]

$\Delta E_{K,roll,i}$ is the energy required to sustain the rolling motion of the wheel during the i-th stroke on pedal of the considered sprint phase (fig. 1.c). The rolling motion was assumed to have the following sinusoidal law:

$$\varphi(t) = \varphi_0 \cdot \sin\left(2 \cdot \pi \cdot f_\varphi \cdot t\right) \tag{4}$$

As explained better in what follows, the value of rolling amplitude φ_0 was assumed, the value of rolling frequency f_φ was estimated by field data analysis.

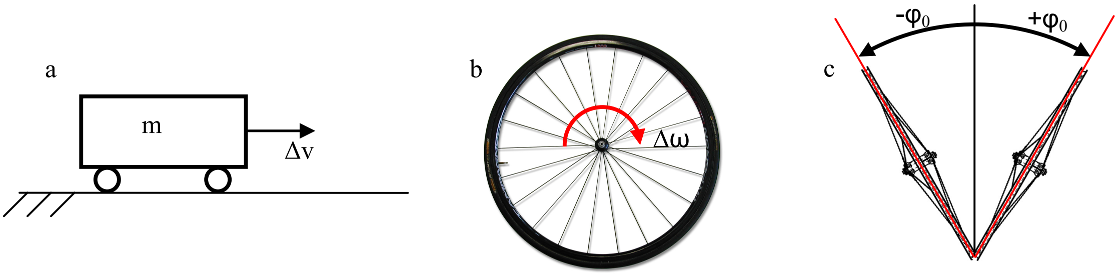

Fig. 1. (a) Wheel model for the computation of the translational kinetic energy increment; (b) schematic of the wheel motion component which causes the rotational kinetic energy increment; (c) schematic of the wheel rolling motion which causes the rolling kinetic energy absorption.

- **Torsional deformation work**

$$\Delta W_{D,torx,i} = \frac{1}{2} \frac{\Delta M_{D,i}^2}{k_{torx}} \tag{5}$$

M_D = drive torque acting at rear hub axis [Nm].
$k_{torx} = M_D/\vartheta$ wheel torsional stiffness [Nm/rad].

$\Delta W_{D,torx,i}$ is the work needed during the i-th stroke on pedals to obtain the torsional elastic deformation of the rear wheel (only rear wheels have a torsional deformation during a sprint). To better understand this phenomenon, we can consider a model with the rear wheel constrained at its external circumference (figure 2a), the application of the driving torque M_D at the rear wheel hub causes the wheel torsional deformation θ. During the i-th stroke on pedal, ΔM_{Di} is defined as the difference between the torque peak and valley as showed in figure 2b.

A complete torque-deformation cycle related to one stroke on pedals can be qualitatively represented as in figure 2c. It is divided into two consecutive phases, the firsts phase is characterized by a torque increase, the second one by a torque decreases. The deformation work $\Delta W_{D,torx,i}$ involved during the first phase, caused by the wheel elastic deformation, is partially returned to the bicycle/cyclist system during the decreasing torque phase due to the wheel elastic rebound. The returned energy E_{ret} is the difference between the deformation work $\Delta W_{D,torx,i}$ and the energy dissipated E_{diss} by the wheel during the torque cycle.

$$E_{ret} = \Delta W_{D,torx} - E_{diss} \tag{6}$$

The return of energy is not an instantaneous phenomenon; therefore an experimental study would be necessary for verifying if its contribution is entirely, partially or not at all useful for the bicycle motion. The estimation of the energy dissipated E_{diss} requires the data concerning the wheel damping behavior. Since during the work these data were not available for the research team, the returned energy E_{ret} was negletted.

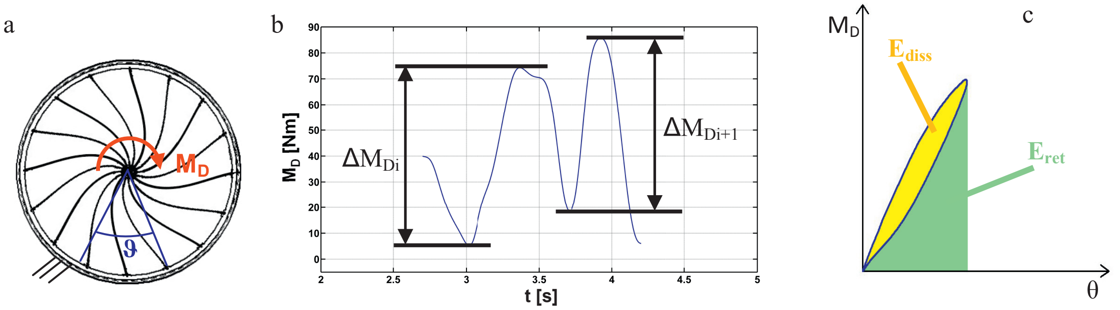

Fig. 2. (a) Schematic of the rear wheel's torsional deformation due to the driving torque; (b) example of the driving torque concerning two strokes on pedal measured during a field test; (c) qualitative representation of a torque-deformation complete cycle and the different energy contributions involved.

- **Side deformation work**

$$\Delta W_{D\,side\,i} = \frac{1}{2}\frac{\left[F_{Wf/rZ} \cdot \sin(\varphi_0)\right]^2}{k_{side}} \tag{7}$$

M_D = drive torque acting at rear hub axis [Nm].
$k_{side} = R_{Wf/rS} / d_S$ wheel lateral bending stiffness [N/m].
$F_{Wf/rZ}$: front/rear wheel static vertical reaction force acting to wheel/road surface point of contact [N].

$\Delta W_{Dside\,i}$ is the work needed during the i-th stroke on pedal to obtain the side elastic deformation of the wheel. The side elastic deformation is caused by the side component $F_{Wf/rS}$ (front/rear) of the vertical force $F_{Wf/rZ}$ acting to the considered wheel. The direction of $F_{Wf/rS}$ is normal to the wheel symmetry plane, considered in the wheel undeformed configuration (figure 3a). During a sprint, the vertical load $F_{Wf/rZ}$ is a dynamic load and it depends from the mass of the bicycle components and of the cyclist, from the bicycle geometry and from the pedaling style of the cyclist. Since at this stage of the work no data about the field tests vertical force $F_{Wf/rZ}$ were available, $F_{Wf/rZ}$ was assumed to be the static vertical load acting to the front or the rear wheel. $F_{Wf/rS}$ is equal to zero if the wheel is in vertical position, it reaches its maximum value at the maximum wheel roll angle φ_0 wich was assumed to be equal to the bicycle roll angle. The energy returned during the $F_{Wf/rS}$ decreasing phase (figure 3c) was again negletted for the same considerations exposed previously for the torsional deformation work.

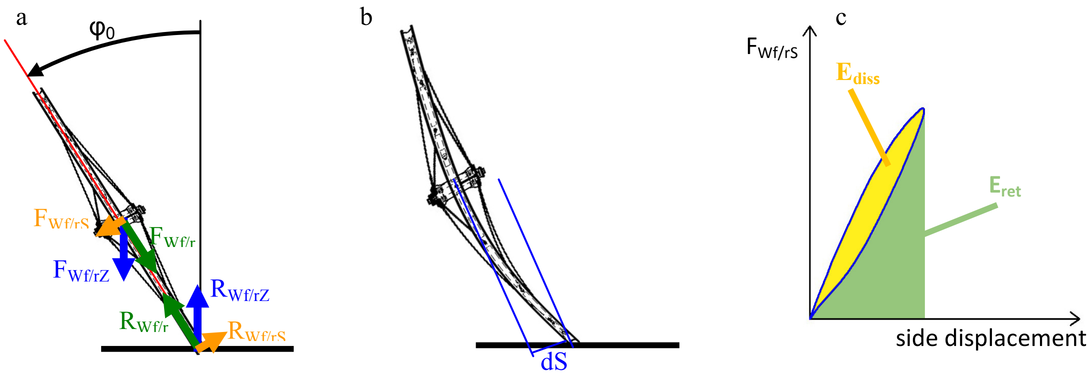

Fig. 3. (a) Forces acting to a front/rear wheel at a roll angle equal to φ0; (b) schematic of wheel side deformation; (c) qualitative representation of a side force - side deformation complete cycle and the different energy contributions involved.

2.3. Reactivity index computation

During a sprint, the total energy E_W^- absorbed by the rear (8) and the front (9) wheel is respectively given by the sum of five and four components.

$$E_{Wr}^- = \Delta E_{K,transl} + \Delta E_{K,rot} + \sum_{i=1}^{n_{ped}} \Delta E_{K,tilt,i} + \sum_{i=1}^{n_{ped}} \Delta W_{D,torx,i} + \sum_{i=1}^{n_{ped}} \Delta W_{D,side,i} \quad [J] \tag{8}$$

$$E_{Wf}^- = \Delta E_{K,transl} + \Delta E_{K,rot} + \sum_{i=1}^{n_{ped}} \Delta E_{K,tilt,i} + \sum_{i=1}^{n_{ped}} \Delta W_{D,side,i} \quad [J] \tag{9}$$

n_{ped} = number of strokes on pedals applied during the sprint phase considered.

The reactivity index $R_{Ef/r}$ of was defined as the inverse of the total energy absorbed by the wheel considered.

$$R_{E\,f/r} = \frac{1}{E_{W\,f/r}^-} \quad \left[\frac{1}{J}\right] \tag{10}$$

The subscript “E” states that the index has been computed with the energetic approach, the subscript “f” or “r” states if the index is calculated for a front or a rear wheel. Higher values of $R_{Ef/r}$ correspond to less energy absorbed by the wheel considered, which means faster response of the wheel to a cyclist sprint action, i.e. higher reactivity.

2.4. Data considered for index computation

The parameters involved in the reactivity index computation were obtained by the analysis of the data acquired during field tests on an instrumented bicycle from which the translational speed variation Δv, the drive torque applied to rear hub ΔM_D, the maximum lateral roll angle φ_0, the roll motion frequency f_φ and the number of strokes on pedals n_{ped} were measured. The sprint action reference consisted in a sprint of a cyclist standing on the pedals at his maximum power, from a starting zero speed with 52/16 transmission ratio, for a travelled distance of 200m. The wheels inertial and stiffness properties were measured during standard wheel laboratory characterization. The vertical load $F_{Wf/rZ}$ acting to front and rear wheel was assumed constant during the sprint. The total vertical load was assumed equal to 900 N and its distribution 30 % to front wheel and 70% to rear wheel.

3. Results and discussion

The reactivity index calculated for three rear wheels different for material, rim profile, spokes number and disposition is showed in figure 4. In this figure, also the normalized values of the mass and stiffness properties (basic engineering characteristics) measured during the usual manufacturer wheels characterization tests are reported. The reported values are normalized in respect to the best value: lowest values for mass and inertia, highest values for stiffness and Reactivity Index.

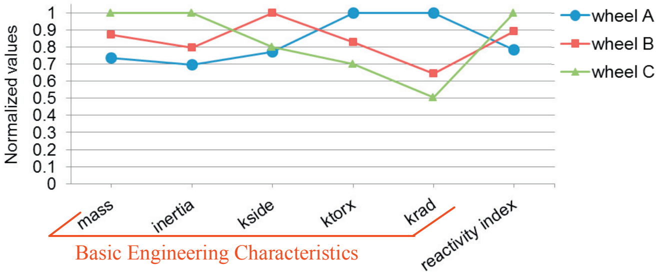

Fig. 4 Values of Basic Engineering Characteristics and Reactivity Index normalized to the best wheel.

Pearson's correlation coefficient between the reactivity engineering index here proposed, calculated for the three wheels, and the reactivity performance score given to the same wheels by 33 cyclists during a subjective evaluation test session resulted to be 0.93. This result was considered to be a good validation of the reactivity index computation method and the overall approach. As it can be appreciated by the values on fig. 6, wheel A, showing the lowest value of the complex reactivity index formerly described, would have been ranked the best wheel if only k_{torx} or k_{rad} would have been considered.

4. Conclusions

A new engineering complex index correlated to wheels reactivity perceived by the cyclists was developed. The Reactivity Index is based on the computation of the energy absorbed by a wheel during a sprint action of the cyclist. The high correlation coefficient 0.93 obtained between the engineering Reactivity Index calculated for three different wheels and the reactivity perceived by the cyclists on the same wheels was considered as a validation of the method developed.

Acknowledgements

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