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A novel dynamometric hubset design to measure wheel loads in road cycling

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Abstract

The aim of this research is to develop a dynamometric road bicycle hubset to enable wheel load measurements while correctly taking into account the end support conditions of the axles. A new hubset design is proposed, providing a way to measure vertical and horizontal forces at each end of the hub axles and to obtain all the ground contact loads acting on the bicycle wheels while pedalling or coasting. This paper presents results for ground contact loads when climbing out of the saddle and for road impact at the wheels.

Keywords: dynamometric hubset; road cycling;

1. Introduction

The importance of using realistic loading data for bicycle design optimization (for example, to reduce mass or for fatigue life considerations) while guaranteeing an adequate safety factor cannot be overemphasised. Because on-road situations such as climbing hills in and out of the saddle, leaning laterally in a hairpin turn and poor road surface conditions are difficult or impossible to replicate in a laboratory, on-road measurements are required to obtain realistic bicycle loading data in these situations. Many transducers designed for in-situ use (outside of the laboratory) in measuring bicycle loads have already been proposed. Several different pedal dynamometers have been described in the literature (Alvarez and Vinyolas [1], Rowe et al. [2], Reiser et al. [3], Drouet et al. [4]) as well as dynamometric seatposts and handlebars (Bolourchi and Hull [5]). To the authors' knowledge, only one dynamometric hubset has been reported in the literature (De Lorenzo and Hull [6]). It was designed to obtain two of the four ground contact reaction loads acting on a bicycle wheel while either coasting or braking and was intended for off-road cycling use. The aim of our research is therefore to develop a new dynamometric hubset design enabling us to obtain all the ground contact reaction loads at the front and rear wheels. These loads consist of two

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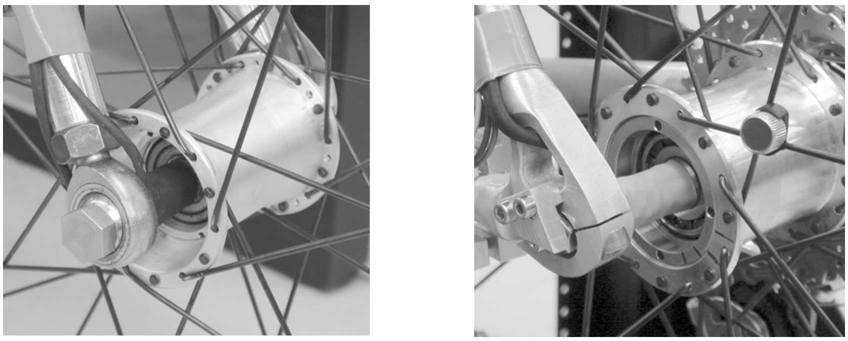
forces in the plane of the bicycle (the tangential force $F_{W\,x}$ and the radial force $F_{W\,z}$), one lateral force $F_{W\,y}$ and one moment $M_{W\,z}$ (see Fig. 3a).

In designing the proposed dynamometric hubset, specific requirements are addressed. One of them is that the dynamometric hubset must be able to withstand high-magnitude ground contact reaction loads as well as high-force pedalling. Even with a high load capacity, the hubset must accurately measure loads throughout the loading range. Using the hub axle as the instrumented component of a hub dynamometer (De Lorenzo and Hull [6]) provides two main advantages: (1) the axle senses all four ground contact reaction loads; (2) with its cylindrical shape and by being a non-rotating part, the axle allows for standard strain gauge instrumentation and cabling. However, caution must be taken to adequately relate the measured deformation of the hub axle to the loads at the fork and frame dropouts and to the ground contact reaction loads. The deformation of the hub axle depends on its end support conditions, which are imposed by local fork and frame stiffness. Therefore, another design requirement is to correctly take into account the end support conditions of the hub axle. Considering that the dynamometric hubset is intended for road cycling use, its mass should also be as small as possible.

2. Methods

One of main design characteristics of the dynamometric hubs (Fig. 1) is that they are supported at each axle end by a spherical bearing. The spherical bearings enable cancellation of dropout moment components and together with the high level of lateral compliance of the fork and frame at the dropouts, they help enforce pinned-pinned boundary conditions as the end support conditions of the axles. The hub assembly (Fig. 2) consists of four principal mechanical components: the instrumented axle, the hub body (including the freewheel mechanism for the rear hub), the wheel bearings and the spherical bearings. The wheel bearings are press fitted on the instrumented axle. This assembly is then slide fitted into the hub body and held in place by a lock ring. The spherical bearings consist of rod ends (model MMF-M12, Aurora Bearing Company, USA) for the front hub and radial spherical plain bearings (model GE10E, SKF Sverige AB, Sweden) for the rear hub. They are fitted on a custom-made fork and frame (Fig. 1). The rear hub freewheel ratchet mechanism (240s road hub, DT Swiss AG, Switzerland) is the only standard part used in the construction of the dynamometric hubset.

To allow for strain gauge installation on the axles, the wheel bearings have been located near the centre of the axles and thus have to withstand higher loads than those on a standard hub. Therefore, we used single row tapered roller bearings (front hub: model 30203, rear hub: model 30303, The Timken Company, USA) in a face-to-face arrangement instead of a ball bearing setup that is normally used in a standard hub. High strength materials were used in the construction of the dynamometric hubset. Heat-treated 17-4 PH stainless steel (yield strength (S_y) = 1250 MPa) was used for the instrumented axles and 7075-T651 aluminium (S_y = 500 MPa) was used for the hub bodies and lock rings. The front and rear hub maximum load is 3000 N applied at each end of the axle in *x-z* plane (Fig. 3b). The mass of the front and rear dynamometric hubs is 334 g and 662 g respectively.



(a) Front hub (b) Rear hub

Fig. 1. Photographs of the dynamometric hubs installed on the custom-made fork and frame

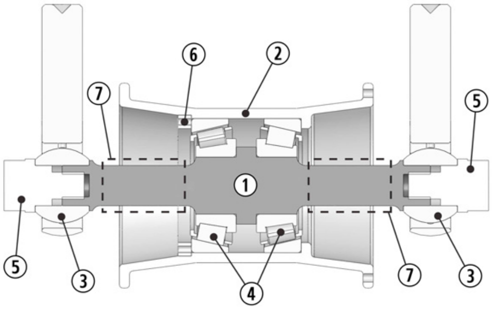


Fig. 2. Sectional view of the front hub with component identification: 1-axle, 2-body, 3-spherical bearings (rod ends), 4-wheel bearings, 5-axle bolts, 6-lock ring, 7-strain gauge instrumented area of the axle

Each hub measures the mutually orthogonal force components: F_{Lx}, F_{Lz} at the left hand side dropout and F_{Rx}, F_{Rz} at the right hand side dropout (Fig. 3b). These forces are measured using a total of sixteen strain gauges per axle (Fig. 2). The strain gauges are arranged in four full Wheatstone bridges. On each side of the hubs, there is one full bridge in the *x-y* plane (F_{Lx}, F_{Rx}) and one in the *y-z* plane (F_{Lz}, F_{Rz}). Theoretically, the position of the strain gauges and their interconnection give bridge signals that are independent of the location of the measured forces as well as insensitive to dropouts moment components (even though they are negligible due to the use of spherical bearings) and to the dropout force acting in the *y* direction. The ground contact reaction loads (Fig. 3a) are calculated using the dropout forces and are given by Equations (1) to (4). The inertia terms (mass multiplied by acceleration) in the equations of motion of the wheels were found to be negligible (<5% of the external loads in the worse case) and therefore have not been included in Equations (1) to (4). F_{Cx} and F_{Cz} are the components of the force exerted on the rear hub by the chain (for the front hub these components must be set to zero). Dimensions *r*, *d* and *e* are respectively the wheel radius, the centre-to-centre distance between the dropouts and the centre-to-centre distance between the chain and the right dropout (rear hub only). To measure chain tension, instrumented force pedals were used (Drouet et al. [4]). In Fig. 3b, only the loads relevant to setting up Equations (1) to (4) are shown.

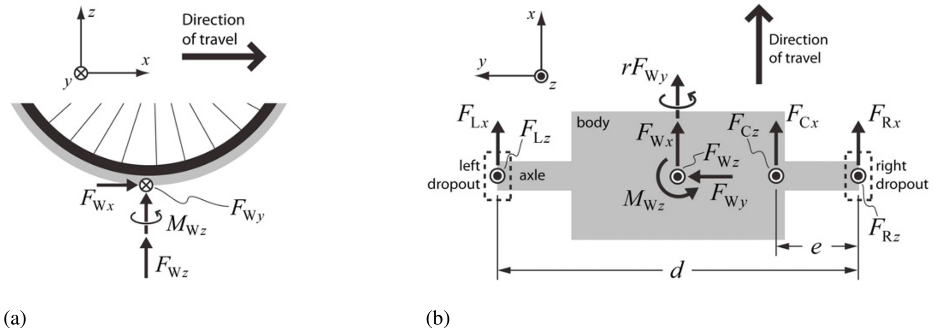


Fig. 3. (a) Ground contact reaction loads acting at the wheel and (b) Hub free-body diagram (Note 1: top view shown; F_{Cx} and F_{Cz} must be set to zero for the front hub; Note 2: The local coordinate system *x-y-z* is attached to the axle)

$$F_{Wx} = -F_{Lx} - F_{Rx} - F_{Cx} \tag{1}$$

$$F_{Wy} = \frac{d}{2r}\left(F_{Rz} - F_{Lz}\right) + \frac{F_{Cz}}{r}\left(\frac{d}{2} - e\right) \tag{2}$$

$$F_{Wz} = -F_{Lz} - F_{Rz} - F_{Cz} \tag{3}$$

$$M_{Wz} = \frac{d}{2}\left(F_{Lx} - F_{Rx}\right) - F_{Cx}\left(\frac{d}{2} - e\right) \tag{4}$$

Measurement data from the dynamometric hubs are collected using a data acquisition system (model pro7, ISAAC Instruments Inc., Canada) attached to a modified backpack carried by the cyclist (Fig. 4). The hubs are wired to the data acquisition system. The hubs' electrical cables are attached to the bicycle frame and converge to an exit point located near the seatpost clamp. The mass of the data acquisition system (including the backpack) is 2.8 kg.

Fig. 4. Cyclist and bicycle equipped with the dynamometric hubset and data acquisition system attached to a modified backpack

Calibration was performed by applying force loads at each end the hub axles to measure the direct sensitivity of the in-plane loads (F_{Lx}, F_{Lz} F_{Rx} and F_{Rz}) and the calibratable cross-sensitivities (Rowe et al. [2]). The force loads were applied by increments of 89 N to a maximum of 445 N. The calibratable sensitivity matrix (V/N, normalized for gain and input voltage) for the front and rear hub is given by Equations (5) and (6) respectively. Considering the high-magnitude axial stiffness of the axles, the non-calibratable cross-sensitivity associated with the dropout force in the *y* direction was not found to be an issue. For the measured forces, linearity is very good ($R^2 > 0.997$) and hysteresis is small.

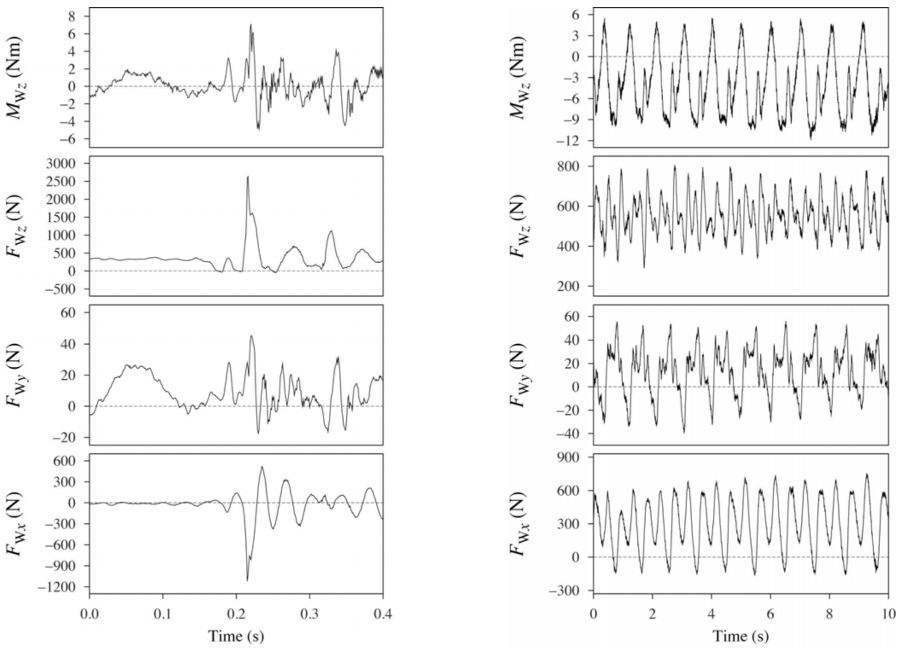
$$\begin{bmatrix} V_{Lx} \\ V_{Lz} \\ V_{Rx} \\ V_{Rz} \end{bmatrix} = \begin{bmatrix} 3.945E-04 & -9.669E-06 & 2.766E-08 & 2.168E-08 \\ 1.592E-05 & 3.934E-04 & 2.128E-08 & 4.656E-08 \\ 2.377E-08 & 6.961E-08 & 3.867E-04 & -6.721E-07 \\ 2.574E-08 & 1.228E-08 & -4.247E-07 & 4.002E-04 \end{bmatrix} \begin{bmatrix} F_{Lx} \\ F_{Lz} \\ F_{Rx} \\ F_{Rz} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} V_{Lx} \\ V_{Lz} \\ V_{Rx} \\ V_{Rz} \end{bmatrix} = \begin{bmatrix} 4.382E-04 & -3.445E-06 & 5.124E-08 & -2.409E-08 \\ 1.668E-05 & 4.406E-04 & 1.738E-08 & 7.105E-08 \\ 3.460E-08 & 1.726E-08 & 4.377E-04 & 6.477E-05 \\ -6.318E-08 & 7.579E-08 & -6.437E-05 & 4.379E-04 \end{bmatrix} \begin{bmatrix} F_{Lx} \\ F_{Lz} \\ F_{Rx} \\ F_{Rz} \end{bmatrix} \tag{6}$$

Using different combinations of ground contact loads, the maximum total root mean square error of the dynamometric hubset was found to be 2.0% FS (Full Scale). The hysteresis was also determined from the calibration data where we found that hysteresis introduced a maximum error of 0.9% FS. The natural frequency along the *x* and *z* axis was determined using the hub stiffness and assuming one-third and two-thirds of a total mass of 90 kg (bicycle and cyclist) for the front and rear hubs, respectively. The natural frequencies for both directions were about 245 Hz for the front hub and 140 Hz for the rear hub.

3. Results

Different on-road measurement sessions were carried out, demonstrating the ability of the dynamometric hubset to provide relevant information. The test conditions consisted of a 75 kg cyclist and a bicycle equipped with the dynamometric hubset (with 32-spoke road rims and 23 mm section tyres inflated to 8 bars) and the instrumented force pedals used to measure the tension force in the chain. The total mass of the system was 90 kg and all the signals were recorded at a sampling rate of 1 kHz. Sample ground contact reaction loads for two segments of the data collected are shown: at the front hub during road impact while coasting (Fig. 5a) and at rear hub when climbing out of the saddle (Fig. 5b). In Fig. 5a, one can see that $F_{W\,x}$ and $F_{W\,z}$ reached -1100 N and 2600 N respectively (resultant force of about 2800 N) during the road impact occurring at 0.21 s. In Fig. 5b, the cyclic and alternate load patterns associated with an out of the saddle climbing effort are easily identifiable.



(a) (b)

Fig. 5. Ground contact reaction loads measured (a) during road impact while coasting (front hub) and (b) when climbing out of the saddle (rear hub)

4. Discussion

One of the design requirements for the dynamometric hubs is that they be able to withstand the loads encountered in a variety of situations, including the most critical case: impacts caused by cracks or potholes in the road. As can be imagined, the severe consequences for the cyclist in the event of mechanical failure of the hubs during hard cornering and high-speed descent are such that this design criterion is an important safety issue. Finite elements analysis (FEA) was used to evaluate stress levels at the hubs.

Enforcing pinned-pinned boundary conditions by means of spherical bearings allowed us to correctly take into account the end support conditions of the axles otherwise imposed by local fork and frame stiffness. However, due to the pinned-pinned boundary conditions, the measured dropout forces do not correspond to the dropout forces encountered using standard hubs and standard dropout clamping conditions. Moreover, no information is provided by the dynamometric hubset on the moment components at the dropout that are normally present with standard hubs. From a bicycle design standpoint, this situation did not prove to be a problem since the dynamometric hubset provides all the ground contact reaction loads. Using these loads as input for a finite element model that includes standard wheels, frame and fork, we were able to conduct adequate and realistic FEAs required for fork and frame design and optimization.

During the dynamometric hubset design process, FEA was used to optimise the area moment of inertia of the instrumented area at the front and rear axles in order to increase hubset sensitivity. It was also used to determine the corner radius at each end of the instrumented area of the axles. The stress concentration in the vicinity of these radii was taken into account to determine the location of the strain gauges and to numerically ensure low cross-sensitivities. FEA was used once more to ensure that the vertical and lateral deflections of the fully mounted wheel with dynamometric hub, rim and spokes are comparable to those of a standard wheel. This was necessary to guarantee proper functioning with a standard brake setup and normal riding sensitivity for the cyclist. Moreover, the use of high strength materials allowed us to reduce the dynamometric hubset mass, which is important, considering the low mass of a typical high end road bicycle.

The accuracy of the dropout forces was established through calibration by evaluating the direct sensitivity and by measuring the influence of the other load components. The direct cross-sensitivity between measured forces ($F_{\mathrm{L}\,x}$, $F_{\mathrm{L}\,z}$) and ($F_{\mathrm{R}\,x}$, $F_{\mathrm{R}\,z}$) is small. It has been taken into account using a calibratable sensitivity matrix and does not contribute significantly to measurement error. The first natural frequency of 245 Hz for the front hub and 140 Hz for the rear hub is high enough to assume a dynamic flat response of the instrumented hubs within the operational measured frequency band of interest between 0-30 Hz.

5. Conclusion

In this paper, we presented a dynamometric road bicycle hubset that enables wheel loads to be measured while correctly taking into account the end support conditions of the axles. We were thus able to accurately measure vertical and horizontal forces at each end of the hub axles and to obtain all the ground contact loads acting on the bicycle wheels while pedalling or coasting. As shown by the measurement results presented, this dynamometric hubset is a valuable tool for providing meaningful and realistic on-road loading data for the bicycle designer.

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