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Development of a three-load component instrumented stem for road cycling

Jean-Marc Drouet[a,a*], Yvan Champoux[a]

[a]Mechanical Engineering Department, VélUS Group, Université de Sherbrooke
2500, boulevard de l'Université, Sherbrooke (QC) J1K 2R1, Canada

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Abstract

The aim of this research was to develop an instrumented road bike stem to enable *in situ* measurements of static and dynamic loads transmitted through the stem-handlebar connection. Our stem is instrumented with twelve strain gauges and enables measurement of the vertical force and two moment components. Calibration and *in situ* measurements demonstrated that the instrumented stem provides accurate measurements for small and large loads. This paper presents the results for stem loads when climbing a hill out of the saddle and during road impact.

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Keywords: Instrumented stem; 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]). Dynamometric hubs,

* Corresponding author. Tel.: +1-819-821-8000 ext. 61345; fax: +1-819-821-7163.
E-mail address: Jean-Marc.Drouet.@USherbrooke.ca.

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seatposts and handlebars have also been described (Bolourchi and Hull [5], De Lorenzo and Hull [6], Drouet and Champoux [7]). To the authors' knowledge, one instrumented stem has been reported in the literature (Champoux et al. [8]). It was designed to obtain vertical force only, was made out of a standard cast aluminium stem and was used indoors for front wheel impact monitoring on a bicycle treadmill. The aim of our research is therefore to develop a new instrumented stem design enabling us to obtain *in situ* measurements of the three most significant loads (for the bicycle designer) transmitted through the stem-handlebar connection. These loads consist of the vertical force, the twisting moment and the moment acting in the vertical plane. In designing the proposed instrumented stem, specific requirements are addressed. One of them is that the instrumented stem must be able to withstand high-magnitude loading associated with road impact and high-power sprinting. Another requirement is that, even with a high load capacity, the stem must accurately measure static and dynamic loads throughout the loading range.

2. Methods

One of the main design characteristics of the instrumented stem (Fig. 1, Fig. 3) is that it is geometrically and dimensionally similar to a standard stem. This is due to the fact that a stem is a beam-like structure and is therefore well suited for strain gauge instrumentation to start with. The instrumented stem consists of three principal mechanical components: the fork steerer tube collar, the handlebar collar, and the instrumented middle section. These components are made of 6061-T6 aluminium (S_y = 250 MPa) and welded together to form a rigid assembly. The middle section of the stem is a thin-walled seamless tube with a circular cross-section. The stem can be used with a standard fork (1.125 in. steerer tube diameter) and handlebar (1.25 in. clamp diameter), and therefore does not require that any modifications be made to the bicycle. The stem angle is 73° which causes the middle section to be parallel with the ground when the stem is mounted on our test bicycle. The stem length is 130 mm and its mass is 260 g.

The stem measures the vertical force F_z and the mutually orthogonal moment components M_x and M_y using a total of twelve strain gauges (Fig. 2, Fig. 3). The measurement origin is coincident with the geometric centre of the stem-handlebar connection. The strain gauges are arranged in three full Wheatstone bridges. There are two full bridges in the x-z plane (bridges #1 and #2) and one full bridge in the x-y plane (bridge #3). Theoretically, the position of the strain gauges and their interconnection give bridge signals that are insensitive to loads that are not to be measured.

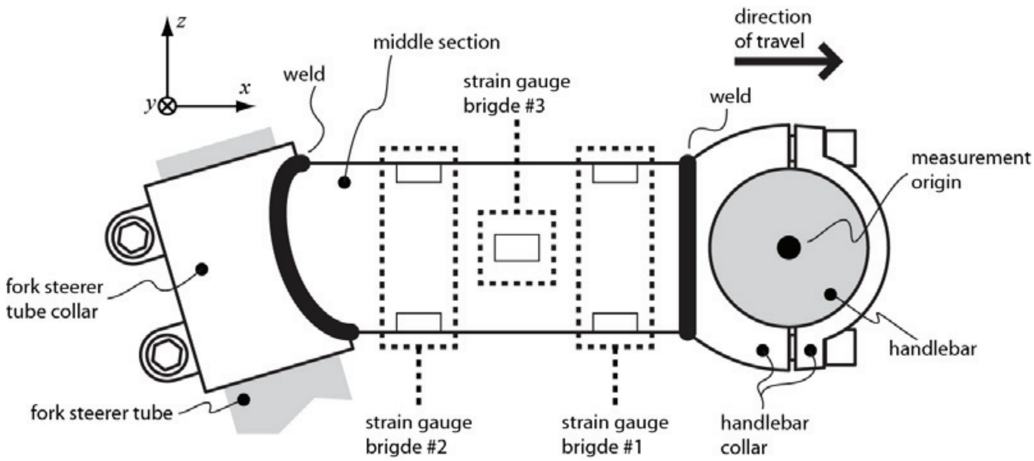

Fig. 1. Side view of the instrumented stem with strain gauges bridges and measurement origin identification

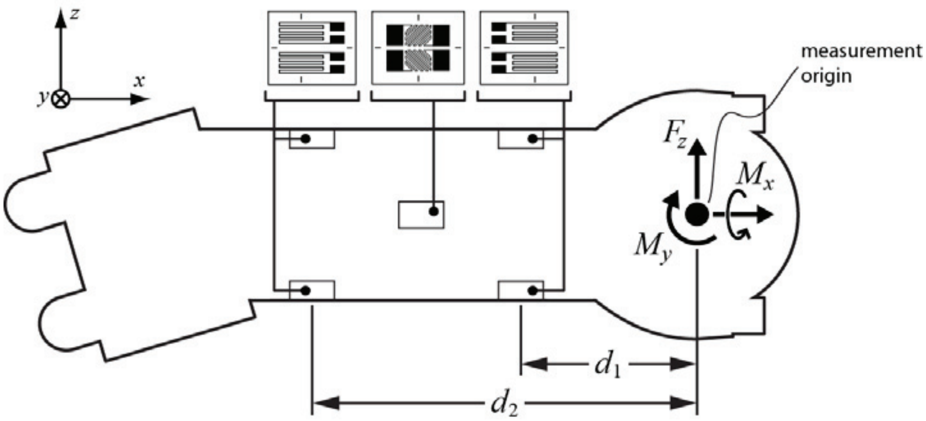

Fig. 2. Side view of the instrumented stem with measured loads, location of bridges #1 and #2, and strain gauge identification

The signals from bridges #1 and #2 are proportional to bending moment F_zd_1-M_y and F_zd_2-M_y respectively. Dimensions d_1 and d_2 (Fig. 2) are the centre-to-centre distance between the measurement origin and the strain gauges for bridges #1 and #2 respectively. Measurement of F_z and M_y is therefore not mechanically decoupled. Dual-pattern strain gauges are used for bridges #1 and #2 (EA-06-125PC-350, Vishay Precision Group Inc., Fig. 2). Bridge #3 provides the twisting moment M_x using two two-element 90° strain gauges (EA-06-125TK-350, Vishay Precision Group Inc., Fig. 2).

Measurement data from the instrumented stem is collected using a data acquisition system (model pro7, ISAAC Instruments Inc., Canada) attached to a modified backpack carried by the cyclist (Fig. 4). The stem is wired to the data acquisition system. Its electrical cables are attached to the bicycle frame (top tube) 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. 3. Photograph of the instrumented stem

Fig. 4. Cyclist equipped with the data acquisition system attached to a modified backpack

Calibration was performed by applying force and moment loads at the measurement origin to measure the direct sensitivity of loads F_z, M_x and M_y, and both the calibratable and non-calibratable cross-sensitivities (Rowe et al. [2]). The calibratable sensitivity matrix (V/N or V/Nm, normalized for gain and input voltage) and the non-calibratable sensitivity matrix (V/N or V/Nm, normalized for gain and input voltage) are given by equations (1) and (2) respectively.

$$\begin{bmatrix} V_{Bridge\#3} \\ V_{Bridge\#1} \\ V_{Bridge\#2} \end{bmatrix} = \begin{bmatrix} 9.73\text{E-}02 & 3.70\text{E-}04 & -4.82\text{E-}05 \\ -4.04\text{E-}04 & -1.45\text{E-}01 & 7.19\text{E-}03 \\ -1.29\text{E-}03 & -1.41\text{E-}01 & 1.20\text{E-}02 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ F_z \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_{Bridge\#3} \\ V_{Bridge\#1} \\ V_{Bridge\#2} \end{bmatrix} = \begin{bmatrix} 3.70\text{E-}05 & -2.00\text{E-}04 & 3.68\text{E-}03 \\ 9.30\text{E-}06 & -5.45\text{E-}05 & 8.71\text{E-}04 \\ 4.35\text{E-}05 & -1.65\text{E-}04 & -8.79\text{E-}04 \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} \tag{2}$$

Using the extreme loading range indicated in Table 1, the maximum total root mean square error of the instrumented stem was found to be 1.6% FS (Full Scale). The hysteresis was also determined from the calibration data where we found that hysteresis introduced a maximum error of 1.0% FS. For the measured force and moment components, linearity is very good ($R^2 > 0.99$). A first natural frequency of 223 Hz was determined using the stem stiffness and assuming one-third of a mass of 75 kg (the cyclist).

Table 1. Stem loading range for the evaluation of the direct sensitivities and the cross-sensitivities

Load component	Load range Min	Max
F_x (N)	-1338	1338
F_y (N)	-1338	1338
F_z (N)	-1000	1000
M_x (Nm)	-150	150
M_y (Nm)	-150	150
M_z (Nm)	-190	190

3. Results

Different on-road measurement sessions were carried out, demonstrating the ability of the instrumented stem to provide relevant information. The test conditions consisted of a 75 kg cyclist and a bicycle equipped with the instrumented stem. All the signals were recorded at a sampling rate of 1 kHz. Sample stem loads for two segments of the data collected are shown below: during road impact while coasting (Fig. 5a) and when climbing a hill out of the saddle (Fig. 5b). Fig. 5a indicates that F_z, M_x and M_y reached -790 N, -32 Nm and 135 Nm respectively 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. In both cases, the cyclist was holding the bicycle near or at the brake hoods without changing hand position. This explains why the ratio M_y/F_z is fairly constant (-0.17 and -0.14 for Fig. 5a and Fig. 5b respectively). The absolute value of this ratio gives an estimate of where the cyclist's hands are located from the measurement origin along the *x* axis (in meters).

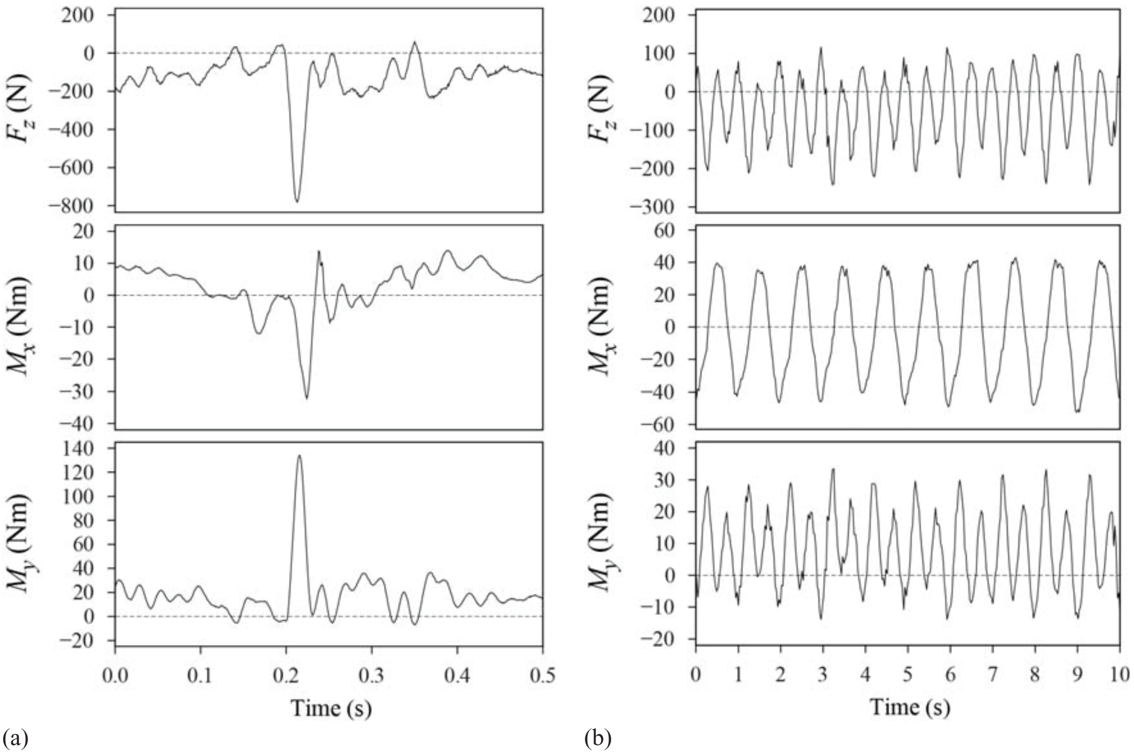

Fig. 5. Stem loads measured (a) during road impact while coasting and (b) when climbing a hill out of the saddle

4. Discussion

One of the design requirements for the instrumented stem is that it 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 serious consequences for the cyclist in the event of mechanical failure of the stem during hard cornering and high-speed descent are such that this design criterion is a vital safety issue. Finite elements analysis (FEA) was used to evaluate stress levels in the stem.

The stem is one of the most straightforward bicycle components to instrument with strain gauges. However, when designing and building an accurate instrumented stem, the importance of (1) maximizing the direct sensitivities while simultaneously (2) minimizing the non-calibratable cross-sensitivities cannot be overemphasized. For the proposed instrumented stem, the following steps have been taken in order to fulfil these two objectives.

- The geometric and dimensional tolerances for the middle section have been tightly controlled.
- FEA was used to evaluate the stress concentration in the vicinity of the welds and also to evaluate the strain field in the middle section of the stem to determine the optimal location of the strain gauges for bridges #1 and #2. This is a most critical step because these bridges must be as far apart as possible from one another to maximize the direct sensitivity and because they must be kept out of the disturbance of the welds over the strain field which is responsible for non-calibratable cross-sensitivity.

The first natural frequency of 223 Hz for the instrumented stem is comparable to that of a standard stem of the same size and material. This can be explained by the fact that the instrumented stem is geometrically and dimensionally similar to a standard aluminium stem, therefore its dynamic behaviour is also similar. From a load measurement standpoint, this means that even if dynamic amplification is present (in field conditions with cyclist holding the handlebar), the dynamic load measurements provided by the stem will be realistic within the frequency bandwidth of interest (0-100 Hz). This is one major advantage over instrumented bicycle parts that are structurally significantly different from their standard counterparts (ex.: pedals [1-4], hubs [7]).

The accuracy of the measured force and moment components was established through calibration by evaluating the direct sensitivity and also by measuring the influence of the other load components. Extreme loadings were considered and it was established that the influence of non-measured loads is small. The direct cross-sensitivity between measured load components is also small and does not contribute significantly to measurement error.

5. Conclusion

In this paper, we presented an instrumented road bike stem that enables *in situ* measurements of loads transmitted through the stem-handlebar connection. With its similar geometry, dimensions and dynamic behaviour to those of a standard stem, the instrumented stem is functionally and structurally equivalent to its standard counterpart, allowing us to obtain realistic measurement of dynamic loads within the frequency bandwidth of interest (0-100 Hz). As shown by the measurement results presented, the instrumented stem is a valuable tool for providing meaningful and realistic on-road loading data for the bicycle designer.

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