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Technique to Measure the Dynamic Behavior of Road Bike Wheels

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ABSTRACT

In the quest to improve comfort in road cycling, a primary concern of the bike manufacturing industry is the vibration generated by the road and transmitted to the cyclist's hands and buttocks. The bike wheels are considered to be one of the major components contributing to the bike's vibration isolation. In this paper, we describe a technique that uses the measurement of a blocked force at the hub. A road simulator was used to impose a controlled white noise vertical displacement under the tire. Measurements were taken of the force under the tire and the blocked force at the wheel hub. Six different wheels were tested. When the force was applied at different locations on the wheel, some of the wheels showed important spatial variations of the blocked force. The results show that this technique is successful in differentiating and ranking the wheels. Each wheel was also characterized by its radial static stiffness. Preliminary results show that there is poor correlation R^2= 0.41 between radial static stiffness and the blocked force at the dynamic hub.

Introduction

Over recent decades, several measurement techniques have been developed to enhance cycling performance, ranging from rider performance measurements to in situ load and stress measurements on the bike frame and components. Rider comfort has also emerged as a significant performance issue. Devoted cyclists spend hundreds of hours each year on their bikes, thus justifying a desire for better comfort. Vibrations generated by road surface defects are a major source of discomfort, fatigue and disincentive to ride; therefore the ability to filter these vibrations is paramount. Designing a road bike with comfort in mind is a major challenge, because contrary to other types of bicycles (i.e. mountain bikes), road bikes have no suspension system: isolation from vibrations therefore depends mainly on the dynamic behavior structure which is characterized by a modal analysis of the full bike, in [1] and [2]. Because of the complexity and sheer number of components on a bicycle, each part must be studied individually in order to better understand and improve the full assemblage.

Road bike wheels are often considered to be one of the components with the greatest influence on cyclist comfort. For one thing, the wheels are in direct contact with the source of excitation: the road surface. So far, the only measurement that has been used to characterize and compare wheels has been a static quantity: the static radial stiffness. Note that in this paper, a bike wheel is composed of a hub, spokes, a rim, and a tire or tube.

The purpose of the research reported in this paper is to experimentally characterize the dynamic behavior of road bike wheels. The specific objectives are (1) to develop a test rig to measure the hub transmitted force and static radial stiffness of road bike wheels; (2) to experimentally measure and analyze these quantities using several wheels in order to disclose intra and inter variability; and (3) to investigate if static radial stiffness could be correlated to the transmitted force at the hub.

Materials and Methods

Figure 1 provides a schematic diagram of the test rig developed for studying wheel dynamic characteristics. The dynamic wheel test rig measures the blocked force at both ends of wheel axle. These ends are respectively clamped to a force transducer (Sensortronics 60001 S-Beam, capacity: 1000 lb) to measure transmitted vertical force. Both transducers are clamped to a very stiff rigid structure connected to the ground in order to measure the hub axle vertical blocked forces. An 8 channels LMS SCADAS Mobile data acquisition system was used and the data was analysed using LMS Virtual.lab software package

A road simulator is used to impose controlled vertical displacement under the tested wheel. The test rig uses a horizontal swing arm rotating freely around a pivot. A motion displacement actuator, the D-BOX KAI Kinetron, drives the swing arm. The use of a swing arm allows for stabilizing the push force in the XZ plane and its length is such that near vertical displacement is obtained under the wheel. The displacement of the actuator is measured with an LVDT (Trans-Tek AC LVDT Series 290). A force transducer (Sensortronics 60001 S-Beam, capacity: 500 lb) located under the wheel measures the push force applied to the tire. A half-cylinder element (13 mm in diameter) is attached to the top of a plate and is in contact with the tire. This force-transmitting element allows the simulation of local contact similar to a road bump. The tire pressure is adjusted to 8 bars.

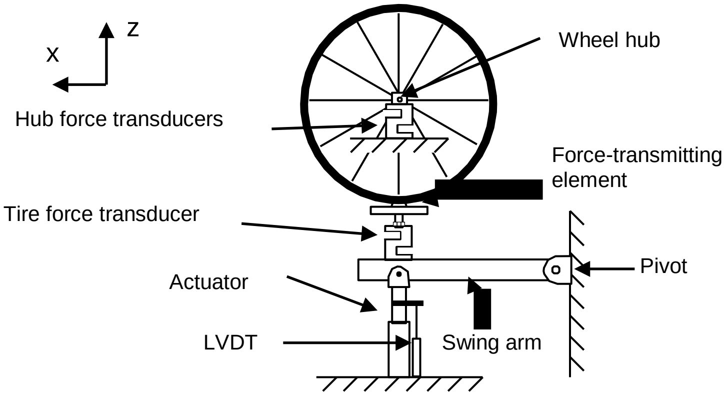

Fig. 1: Dynamic wheel test rig

For the purposes of this paper, only the front wheels were tested. To simulate the typical preload of a 75 kg cyclist, the actuator is positioned to generate a nominal preload force of 250 N on the wheel

In all the tests we conducted, the preload was adjusted to compensate any wheel out of round variation. A white noise signal was provided to the actuator with an average displacement range of ±0.25 mm. A typical displacement power spectrum density (PSD) measured by the LVDT is shown in Fig. 2. The DC component of the curve is due to the preload force. The amplitude response of the actuator drops drastically above 100 Hz. This is caused by the actuator speed limitation. The bandwith of interest is 0-100 Hz, with the knowledge that human sensitivity to vibration diminishes drastically above 100 Hz [3].

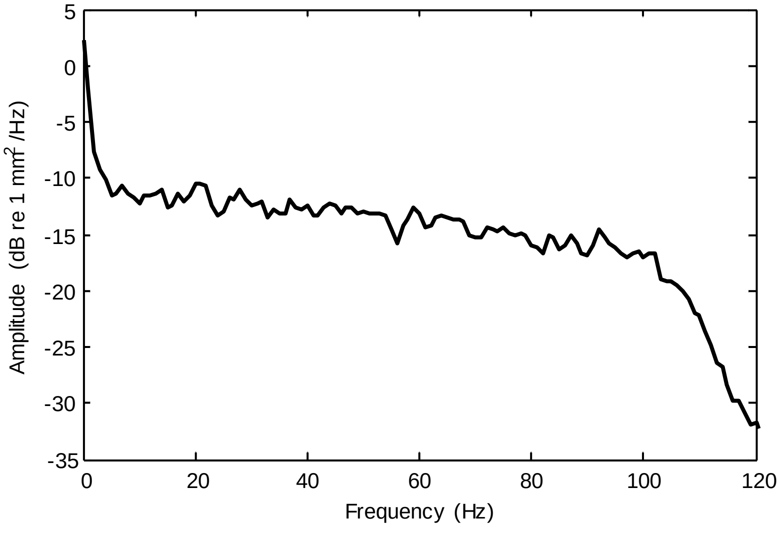

Fig. 2: PSD of the simulator vertical displacement

Wheel force transmission characteristics

Figure 3 illustrates the typical PSD of the total blocked force transmitted by the hub. All the PSDs in this paper are calculated using 60 averages of 1 s segments overlapped at 67%. The curve shows that the wheel has a dynamic amplification between 70 and 100 Hz.

This measurement represents the total force that would typically be transmitted to the front fork, but in this case this measurement is done in a block condition. The root mean square value of the PSD, F_{rms}, is measured for a frequency bandwidth ranging from 2 to 110 Hz, for which there is enough input energy injected in the system by the test rig [4]. This frequency bandwith also allows for the removal of the DC force component.

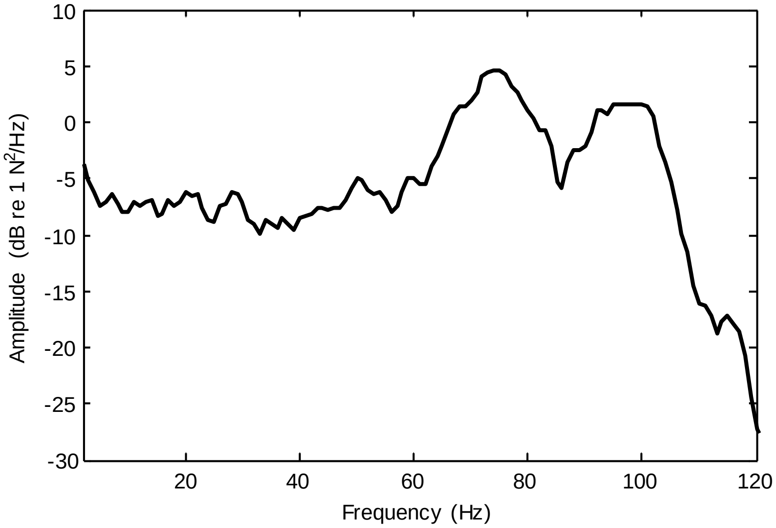

Fig. 3: PSD of the total blocked force transmitted at the hub

We measured the local blocked force F_{rms} at several circumferential locations in order to explore potential variability related to the measurement location. Figure 4 shows the spatial distribution of F_{rms} measured three times at 16 locations evenly spaced around the wheel, on two different wheels. Significant F_{rms} variation around the wheels is easily observed. Wheel *B* (Fig 4b) shows a much greater variation than wheel *A* (Fig 4a). The maximum variation range measured on a single wheel is 25.2%, with a standard deviation of 5.0% relative to the mean value. The mean of all the 16 F_{rms} measured around the circumference for a test is calculated and designated as $\bar{F}_{rms}$. This provides a single number for a test that will ease wheel behavior comparison analysis. The two wheels show very different mean values of $\bar{F}_{rms} = 8.18$ N for wheel *A* and $\bar{F}_{rms} = 6.78$ N for wheel *B*.

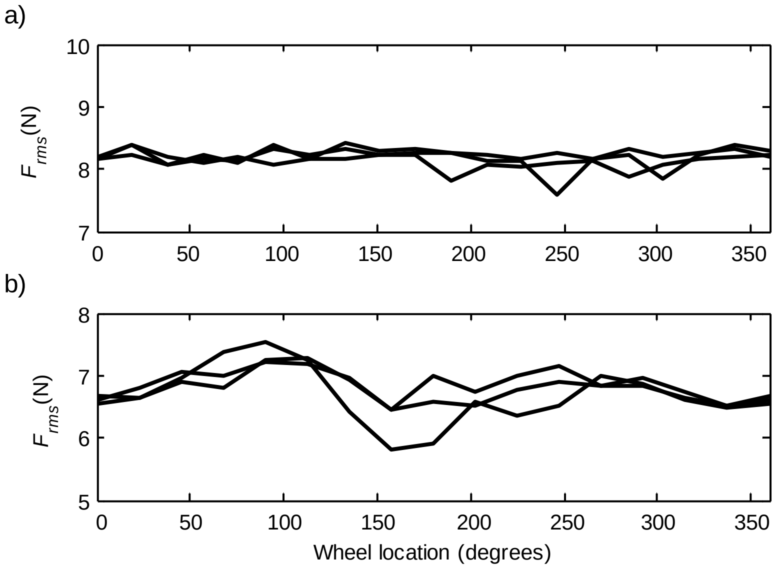

Fig. 4: F_{rms} for different locations around the wheel circumference. The test is repeated three times

a) Wheel *A*: low F_{rms} variability with $\bar{F}_{rms}$ = 8.18 N;

b) Wheel *B*: high F_{rms} variability with $\bar{F}_{rms}$ = 6.78 N

To explore the merit of this new testing technique, it is interesting to quantify the F_{rms} intra-variability using several wheels of the same model. Two same-model front wheels were tested with identical tubes and tires (Fig. 5). The mean difference between the curves is 0.25 N, which represents 3% of the average F_{rms} over all measurement locations.

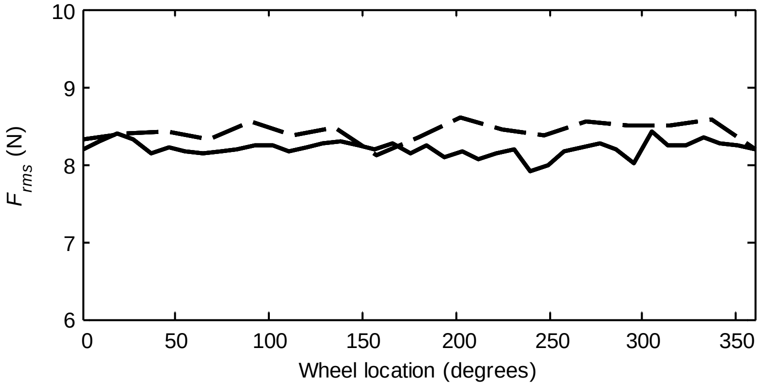

Fig. 5: F_{rms} comparison of two same-model wheels with measurements taken at 16 locations around each circumference:

——Wheel sample *A* $\bar{F}_{rms}$ = 8.18 N and - - - - Wheel sample *B* $\bar{F}_{rms}$ = 8.43 N

Wheel rankings

The ability of the blocked force measurement to differentiate between different wheels was assessed with a test campaign using 5 different wheels. Each wheel was tested 3 times at 16 locations and the mean value at each location is presented for each wheel in Fig. 5. The $\bar{F}_{rms}$ is also presented for each wheel.

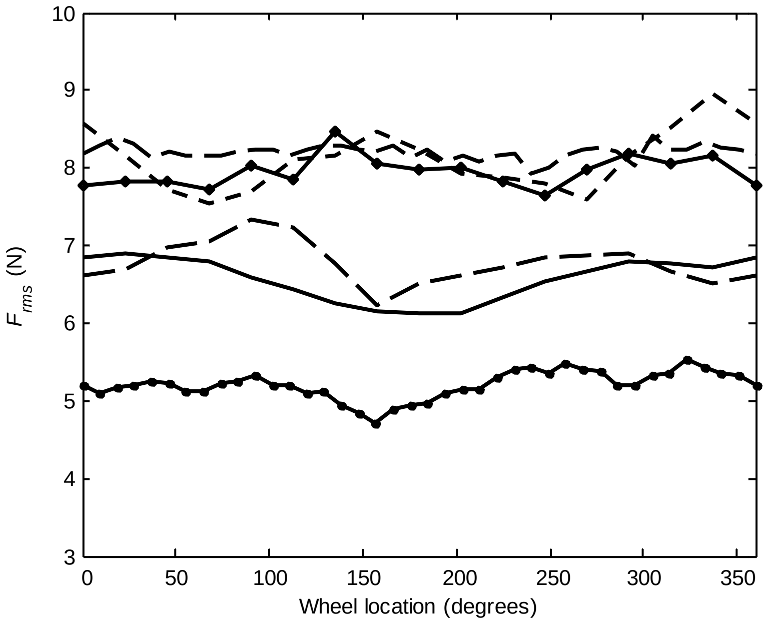

Fig. 6: Hub transmitted force (F_{rms}) for 6 different wheel models:
●—● Wheel 1, $\bar{F}_{rms}$ = 5.20 N, ____Wheel 2, $\bar{F}_{rms}$ = 6.56 N, - - - - Wheel 3, $\bar{F}_{rms}$ = 6.78 N, ◆—◆ Wheel 4, $\bar{F}_{rms}$ = 7.96 N, ____Wheel 5, $\bar{F}_{rms}$ = 8.09 N, - - - - Wheel 6, $\bar{F}_{rms}$ = 8.18 N

A significant difference between $\bar{F}_{rms}$ was found using hypothesis testing with a 5% level of significance. Based on Student's *t* distribution (*t*-test) the equivalence of two $\bar{F}_{rms}$ is rejected when $t_0 > t_{0.05,\upsilon}$. The test was performed based on the fact that the variances between the wheels are not equal and with υ representing the degrees of freedom of the analysis [5]. This hypothesis testing shows that using $\bar{F}_{rms}$, it is possible to differentiate the wheels, except between wheels 4 and 5 and wheels 5 and 6.

Static radial stiffness and dynamic behavior

The static radial stiffness test is commonly used to compare wheels because it is a relatively simple test to perform. One of our research objectives is to investigate if the dynamic behavior of wheels can be correlated to their static radial stiffness.

Static radial stiffness was measured on the wheels using the test rig. A vertical displacement under the tire was imposed by the simulator and measured with the LVDT. The force applied to the tire was simultaneously measured, allowing for direct stiffness calculations. To avoid any viscoelastic or dynamic effect, a total displacement time of 30 s was used with a maximum displacement of 2.5 mm. To avoid local effects and obtain a global characterization of the wheel, static radial stiffness was measured at 16 locations evenly spaced around the wheel. In parallel, the dynamic test protocol described previously was used to provide corresponding hub transmitted force. A 250 N preload force was applied during stiffness measurements.

Static radial stiffness as a function of $\bar{F}_{rms}$ is shown in Fig. 7. According to the value of the coefficient of determination (R^2 = 0.41), linear correlation between the static radial stiffness and the $\bar{F}_{rms}$ cannot be established.

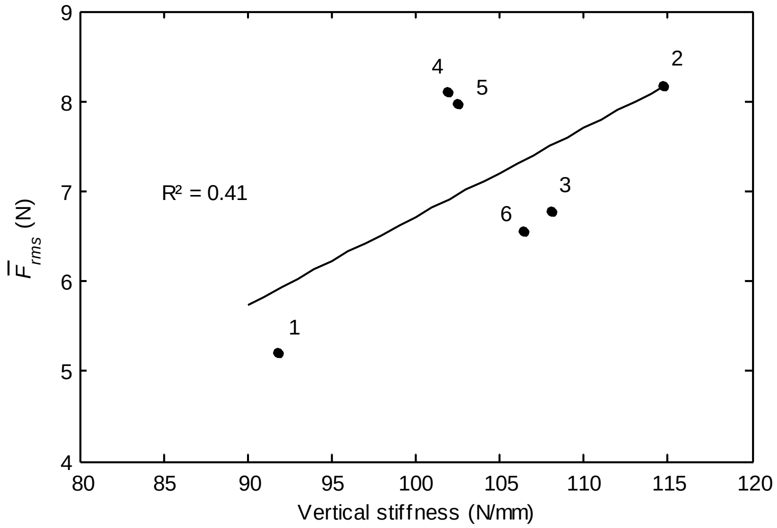

Fig. 7: Static radial stiffness as a function of $\bar{F}_{rms}$ (wheels 1 to 6)

Discussion

Measurement of the force transmitted at the hub generated by displacement imposed over the circumference of the wheel, and the corresponding average value $\bar{F}_{rms}$ for several different wheel models shows that wheels do behave differently and that they do not transmit the same force level. Statistical analysis indicates that this is not du to chance and it allows to differentiate the wheels among them. As well, these measurements require a specific rig. However, this approach still offers a relatively easy way to dynamically evaluate and compare wheel behavior. It was also shown that measurements must be made at several locations around the wheel circumference in order to obtain average values, because wheels may have significant behavior variability around the circomference. This may be related to spoke characteristics tension, assymetry of the rim, or the location of the force relative to the point where the spoke is attached on the rim.

One interesting hypothesis is that the wheel with the lowest $\bar{F}_{rms}$ value is the most comfortable one. However, certain elements must be considered before drawing such a definitive conclusion. The technique uses a blocked force which allows us to make sure that all wheels are tested under the exact same boundary conditions at the hub for the force measurement. A real fork would not apply the same boundary conditions and this will infuence the amplitude of the transmitted force. Although this may not change the ranking obtained with the blocked force situation, further investigation is nevertheless required to explore this aspect. A flat frequency displacement spectrum was used in this paper. It would be useful to use a spectrum that is similar to real road excitation.

The radial wheel stiffness and the $\bar{F}_{rms}$ measurement on the tested wheels did not show good correlation. The vibration transmitted to the cyclist's hands and buttocks is a complex physical issue, and a better understanding of the transmission mechanism of several components must be achieved before a definitive conclusion regarding the relationship between the static radial stiffness of the wheels and cyclist comfort can be reached.

Acknowledgments

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