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Using Power as a Metric to Quantify Vibration Transmitted to the Cyclist

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Abstract

For the purposes of new product development, the cycling industry requires an objective means of ranking bicycle comfort with regard to vibration response. Acceleration is currently the standard metric used in the industry. Absorbed power and transmitted force have recently been proposed as metrics to quantify bicycle comfort. The objective of this paper is to compare the relative merits of these 3 metrics. Measurements were done while comparing 2 bikes tested on a cobblestone road and on a laboratory simulator. Acceleration and absorbed power give the same anticipated results but the absorbed power has several advantages over the other metrics.

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Keywords: *Absorbed power metric; acceleration metric; force metric; bicycle comfort ranking; vibration transmission.*

1. Introduction

Comfort is an important asset in a bicycle for road cyclists who tend to ride for long periods of time. In order to assess bicycle comfort and support the development of new products, engineers must base their judgment on measured quantities (metrics) to quantify the vibration transmitted from contact with the road and felt by the cyclist. In the literature, three metrics are typically used to quantify vibration transmitted to a cyclist: acceleration (Giubilato and Petrone (2012); Hasting et al. (2004); Olieman and Marin-Perianu (2012)), force (Lépine et al. (2012)) and absorbed power (Vanwalleghem et al. (20012)). For comfort assessment, ISO standards (ISO2631 and

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ISO539) propose filtering acceleration signals to provide acceleration root mean square (RMS) values linked to the perception of the vibration. As far as comfort is concerned, absorbed power is believed by some to be a better metric because it takes into consideration the energy exchange between the vibrating structure and the human body (Vanwalleghem et al. (2013); Mansfield and Griffin (1998); Pradko and Lee (1966)). To study the vibrational dynamic behaviour of frames and bike components, tests must be conducted with a cyclist riding the bike. The mass and the damping added to the bike by the cyclist change the bike's dynamic behaviour completely (Chapoux et al. (2007)). Previous laboratory tests have shown that acceleration and force are greatly influenced by the cyclist's natural position sway (Lépine et al. (2013)). Typically, as the force increases at contact points between the cyclist and the bike, the acceleration tends to decrease. The metric used to quantify vibration therefore needs to be as insensitive as possible to the cyclist's position on the bike. Because the absorbed power takes into account force as well as acceleration magnitude and phase, this metric could potentially be unaffected by the position of the cyclist and therefore be a better metric to assess comfort. This paper provides an exploration of the merits of the three metrics: acceleration, force and absorbed power. A systematic comparison was conducted of experimental measurements obtained with two different bicycle models in two riding situations: 1) outdoors, on a sloped cobblestone road and 2) indoors, in laboratory conditions replicating a granular road surface.

2. Methods

This section describes the experimental setups, transducers, experimental protocols, signal acquisition material and the data analysis method used in this study to obtain the results. The methods described below have been approved by the ethics committee of University of Sherbrooke.

- *Outdoor and Laboratory Setup*

Two road excitation types were used to measure the level of vibration transmitted to the cyclist: 1) outdoors on a cobblestone road and 2) in the laboratory using a road excitation simulator. In both setups, the cables, shifters and dangling chain that could hinder the measurement procedure were removed from the bicycles. For outdoor measurements, since the bike cannot be self-propelled without a chain, a sloped cobblestone road was selected (Fig. 1a). The bicycle was thus propelled by the force of gravity, allowing the rider to maintain a stable position thus favoring repeatable measurements. To allow time for the cyclist to stabilize his position, acquisition was initiated 5 s after the cyclist began riding from a standstill. The acquisition period was set at 30 s. To reproduce road excitation in the more controlled environment of the laboratory, 2 Xcite hydraulic shakers (model 1107-4-T/C) were used to impose vertical displacement on the wheels (Fig. 1b). The excitation signals were purely vertical (*z* axis) and were selected to represent the vertical excitation that a bike undergoes when rolling on a granular road. For this purpose, the signals played by the shakers were first recorded with an accelerometer attached to the rear wheel axle of a road bike rolling at a constant speed of 26 km/h on a flat granular road. During the recording process, a cyclist was mounted on the bike and towed by a vehicle - as described by Lépine et al. (2013). Two completely different parts of this recorded signal were taken at the front and rear hydraulic shakers, as preliminary tests showed that uncorrelated signals are more representative of real life excitation (Lépine et al. (2013)). The bicycle was kept vertically stable with bungee cables wrapped around the seat tube and attached to a stationary structure on each side of the bicycle. The bungee ropes were selected to be compliant enough not to affect the vibration measurement, but stiff enough to hold the cyclist and bike in a vertical position.

- *Acceleration and force measurement*

Typically, a cyclist can absorb energy at three contact points (feet, hands and buttocks). Since the level of vibration felt at the feet is four times lower than that perceived at the buttocks (ISO 2631), only the level of vibration transmitted to the hands and the buttocks is considered in this paper. Furthermore, only the vertical axis (*z*) component of the forces, accelerations and power are shown in this paper since most of the measured vibration is in that direction (as indicated by preliminary measurements).

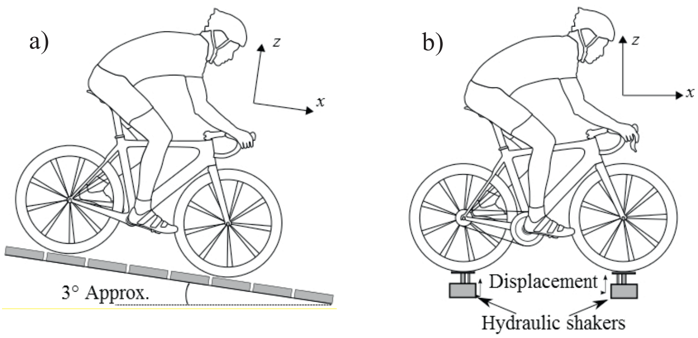

Fig. 1: Road excitation types; (a) Outdoor cobblestone excitation setup (b) Laboratory road simulator excitation setup

To measure the acceleration at the contact points, 3 accelerometers were used: 2 uniaxial (PCB model 352C65) under the brake hoods and 1 multi-axial (PCB model 356A32) on the seat post. To measure the forces at the points of contact, 2 different types of custom-made strain gauge transducers were used: an instrumented brake hood (Fig. 2a) and an instrumented seat post (Fig.2b) (Caya et al. (2012)). Acceleration and force transmitted to the cyclist's hands and measured at the brake hoods are processed with a filter corresponding to human hand sensitivity (ISO5349 hand-arm vibration standard). Fig.2c shows a run example of the acceleration time and frequency response at the right brake hood.

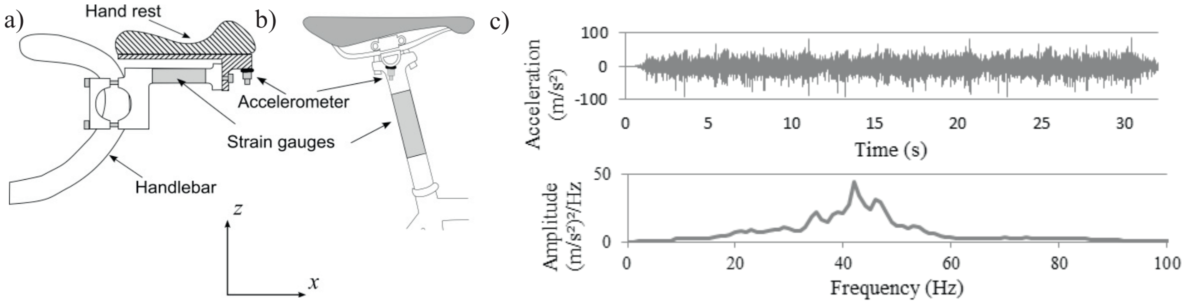

Fig 2: (a) Brake hood force transducer (b) Seat post force transducer (c) Break hood time and frequency response to acceleration

2.1. Signal acquisition and power measurement

For the vibration transmission assessment, we used the transducers to measure the acceleration and force signals using an LMS SCADAS 24 bits acquisition system (model SCR01-08B) at a frequency of 8192 Hz. LMS Test.Lab software was used for data processing. Acceleration and force transmitted to the cyclist's hands and measured at the brake hoods were processed with a filter corresponding to human hand sensitivity (ISO5349 hand-arm vibration standard). Acceleration and force transmitted to the cyclist's buttocks and measured at the seat post were treated with a corresponding filter (ISO2631-1 whole body vibration standard). Note that the ISO filters were designed for acceleration signals but the same filters are also used for the force signal.

The mean absorbed power corresponds to the rate of energy dissipated in heat by the vibration of the human body parts in contact with the bike. This measurement can be done in either the time or the frequency domain. In the time domain, the mean absorbed power P is the time averaged over a number of observation N of the instantaneous power $p_i = F_i v_i$ (F_i and v_i being the instantaneous force and velocity) as given by Eq. (1).

$$P = \frac{1}{N}\sum_{i=0}^{N} p_i = \frac{1}{N}\sum_{i=0}^{N} F_i v_i \tag{1}$$

In the frequency domain (where f represents the frequency), the mean absorbed power is computed using the integration over the frequency range of interest in the real part of the cross-spectrum between the force (F) and velocity (v) as shown in Eq.2.

$$P = \sum_{f=f_{\min}}^{f_{\max}} \mathrm{Re}\left[G_{vF}(f)\right]\Delta f \tag{2}$$

In the frequency domain, it is possible to correct for the phase mismatch between the transducers. This mismatch can be caused by the presence of analog high pass filtering or any electronic delays in the measurement system. Note that the mean power P is calculated using the raw signals of force and velocity and that there is no ISO standard filtering process involved. Since this mean power metric is based on energy content it is believed to be proportional to a level of perception (Pradko and Lee (1966)).

- *Protocol and data analysis*

The same cyclist participated in all tests, riding two different instrumented road bicycles (Bike A and Bike B) that are systematically compared. Bike A is reputed to be much less comfortable than Bike B. When testing outside, eight 30 s excitation runs are done for each bicycle. A 5 min break is given in between each run in order for the cyclist to walk up the hill and rest. A 20 min break is given after eight runs in order to set up the other instrumented bike. When testing in the laboratory, 10 excitation runs of 30 s each are done for each bicycle during which the cyclist keeps a steady position with the help of a visual feedback on the DC vertical force applied on each brake hood.

For the acceleration and force signal, the RMS value is used to represent each run. For absorbed power, a single mean value is used to represent each run. These values are used in an analysis of variance (ANOVA) to evaluate if there is a significant difference in the vibration transmitted to the cyclist by each bike. The ANOVA is done with a 0.05 level of significance, meaning that if the p-value is below 0.05 for a given criterion, the two bikes should be considered significantly different. It should be noted that since the tests were not done in a random order, the test order was included as a covariant in the ANOVA.

3. Results

In Figures 3 to 5, each bar represents the mean of all the run values from a single bike in a single excitation condition (8 run values per bike for outdoor excitation and 10 run values per bike for inside excitation). The graph's vertical axis is the amplitude of the vibration measured in acceleration in Fig. 3, force in Fig. 4 and absorbed power in Fig. 5. The horizontal axis indicates the position of the measurement on the bike (brake hoods or seat post). The error bars represent a 95% confidence interval. The p-values of the comparison test for each transducer are indicated above the bars. The solid bars represent the lab tests and the cross-hatched bars represent the outdoor tests. For a given bike, it is assumed that the lower the metric value is, the fewer vibrations transmitted to the cyclist and thus the more comfortable the bike is.

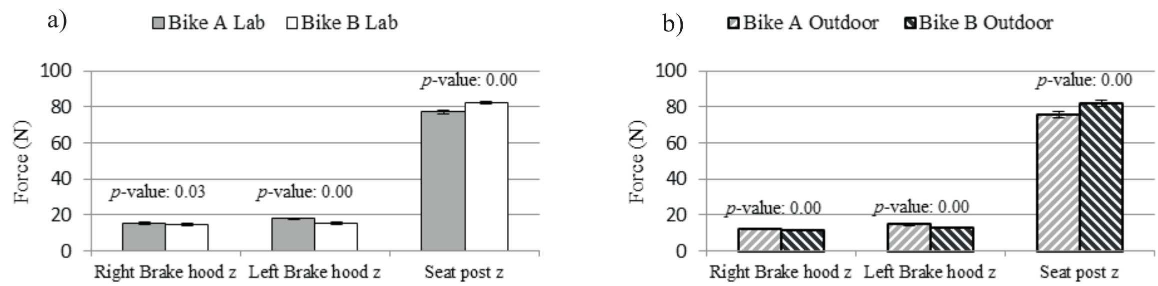

Fig.3: Mean of force RMS run values; (a) 10 runs for laboratory tests; (b) 8 runs for outdoor tests

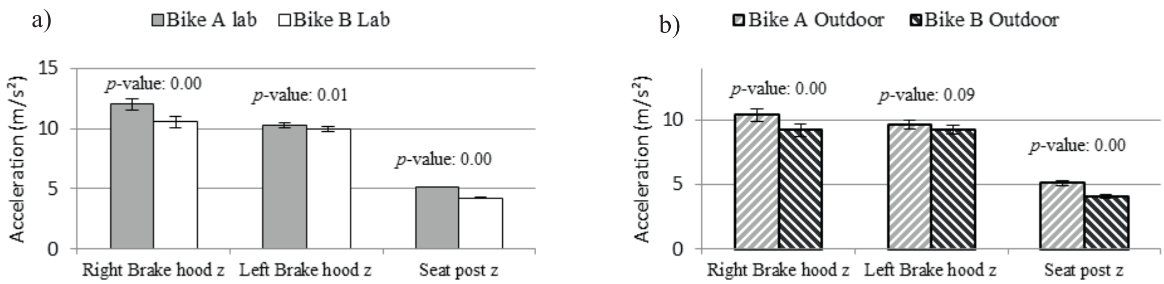

Fig.4: Mean of acceleration RMS run values; (a) 10 runs for laboratory tests; (b) 8 runs for outdoor tests

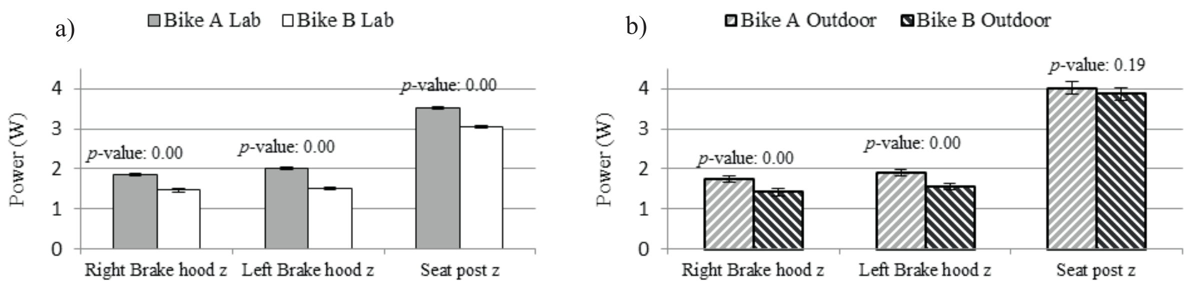

Fig.5: Mean of absorbed power run values; (a) 10 runs for laboratory tests; (b) 8 runs for outdoor tests

In Fig. 3, the force metric suggests that Bike A is less comfortable at the hands, but more comfortable at the buttocks. In Fig. 4, the acceleration metric suggests that Bike A is less comfortable than Bike B at every measurement location. However, the outdoor conditions for seat post measurement suggest a statistically insignificant difference. In Fig. 5, even though outdoor conditions for the right brake hood show a statistically insignificant difference, the absorbed power metric suggests that Bike A is less comfortable than Bike B in the overall analysis.

4. Discussion

The results previously disclosed show that the acceleration and absorbed power measured in Bike B are systematically lower than in Bike A. Based on the assumption that low values for the metrics correspond to a more comfortable situation, this means that Bike B could be considered more comfortable than Bike A. However, the results obtained with the force indicate a less comfortable situation. Both forces and accelerations use the same ISO filters. These filters are commonly used to take into account the perception characteristics of a human body in order to obtain an RMS acceleration magnitude proportional to a perception. However, some researchers argue that ISO filtered acceleration is a poor representation of the vibrations that are actually transmitted to the body (Lundström et al. (1998)). The use of the same filter on the force is not proposed by any ISO standard. In this paper, the decision to filter the force with the same filter was based on the fact that Newton's second law establishes a linear relationship between the force and the acceleration. It is possible that using an ISO filter with force signals is not appropriate for a comfort study. More research needs to be done in this regard. The ISO filters are related to specific body postures and vibration excitation orientations. The cyclist's body position does not correspond exactly to any of the ISO standardized postures. These latter elements substantiate the opinion of the authors and other researchers (Lundström et al. (1998); Mansfield and Griffin (1998)), i.e. that the mean absorbed power is a better metric than acceleration or force to assess comfort. No ISO filtering process is required to measure the absorbed power. The power measurement eliminates the non-correlated noise. Measuring power is nevertheless technically more difficult than measuring acceleration or force alone.

5. Conclusion

The measured acceleration and mean absorbed power at the cyclists' contact points both succeeded in significantly differentiating 2 bikes tested in 2 different configurations. They both identify the same reputedly more comfortable bike. However, the mean absorbed power metric has unique characteristics when compared to the acceleration metric: it does not require the use of an ISO filter; it is a metric based on energy content and noise can be eliminated when using it.

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