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Dynamic calibration of an instrumented bike brake hood in measuring power absorbed by the hands

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Abstract

One of the most significant factors in ride quality in cycling sports are the vibrations generated by road surface defects passing through the bicycle and transmitted to the cyclist's hands and buttocks. To study comfort, one metric that has been put forward is the measurement of the power absorbed at the cyclist's hands. Measuring absorbed power requires the use of the force and the velocity at the hands and provides an overall energy-based quantity. The aim of this study is to dynamically calibrate an instrumented brake hood transducer to measure the power absorbed at the cyclist's hands. Using a base excitation technique involving suspended masses, dynamic calibration of the brake hood was conducted in the 3-100 Hz frequency range, and the force transducer sensitivity and seismic mass were measured. An accelerometer attached to the brake hood enabled measurements of acceleration and calculation of velocity. A frequency-dependent phase mismatch between the force signal and the acceleration was obtained by measuring the accelerance at the hand-bike interface. A device called the Power Calibrator equipped with an impedance head was developed to assess the accuracy of the power measured by the instrumented brake hood. The results show that the instrumented brake hood can accurately measure the absorbed power at the cyclist's hands. Phase mismatch between the force and the velocity signals must be corrected to improve the accuracy of measurements. To implement the measurements, it is recommended that the calculations be done in the frequency domain.

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1. Introduction

Road cycling enthusiasts ride for periods totalling several hundred hours per year. It is therefore not surprising that they are willing to pay extra to obtain a comfortable bike that can filter the greatest possible amount of road vibrations felt at the hands and buttocks. In comfort assessment studies in the transport industry, acceleration is often used to quantify vibration. Acceleration is easy to measure because it merely requires attaching a small and readily available transducer to the structure.

A body part in contact with a vibrating structure dissipates the energy transmitted from the structure in the form of heat. For example, when a cyclist is riding a road bike on a rough road surface, the hands and buttocks absorb the energy transmitted respectively by the handlebar and the saddle. Power is the rate of energy transferred between two structures. A proposed alternative metric to assess comfort is the power absorbed by the human body part at the contact points with the vibrating structure [1]. No filter is required when using the absorbed power [2-3]. Since power is a scalar quantity, it can be calculated when dealing with a complex multi-degree of freedom system to determine human response. Absorbed power has previously been measured on a road bike using an instrumented handlebar [4-5].

In this paper, an instrumented brake hood previously developed to measure cyclist hand force [6] is used. To obtain accurate measurements, the dynamic behavior of the transducer must be taken into account. A direct technique that obtains the amplitude and phase relationship between the force and the acceleration is described. A comparative technique using an impedance head and allowing an in-situ calibration is also presented. A typical absorbed power measurement example is provided. The advantages of calculating the power in the frequency domain are also underlined.

2. The basic principles of power measurement

The time domain average mechanical absorbed power can be measured using the following equation

$$P = \frac{1}{T}\int_0^T f(t)\,v(t)\,dt \tag{1}$$

where T is the integration time, $f(t)$ and $v(t)$ the respective instantaneous force and velocity. In practice, an accelerometer is used to provide the velocity following a time integration of the accelerometer signal.

In the frequency domain and for a frequency span f_{min} to f_{max}, the power is calculated as follows:

$$P = \int_{f_{\min}}^{f_{\max}} \mathrm{Re}\left[G_{fv}(f)\right] df \tag{2}$$

where $\mathrm{Re}\left[G_{fv}(f)\right]$ is the real part of the cross-spectrum $G_{fv}(f)$ between the force and the velocity. The velocity is calculated in the frequency domain by dividing the acceleration spectrum by $j\omega$.

3. Brake hood force transducer

An instrumented brake hood mounted on a road bike was originally designed [6] to measure the vertical transmitted force at the hand of a cyclist. As shown in Fig. 1, the transducer consists of 2 parts bolted together: a hand rest in contact with one of the cyclist's hands, and an aluminum instrumented body attached to the handlebar. The hand rest is connected (bolted) at the right hand side of the instrumented body only. The functioning principle of the transducer is equivalent to a cantilever beam force transducer. The left side of the instrumented body is clamped to the handlebar. The road vibration is transmitted to the handlebar which in turn transmits its motion to the transducer. The vertical force f_2 at the right hand side of the instrumented body pushes on the hand rest. The instrumented zone section has a rectangular shape. A full WheatStone bridge using 1000 Ω strain gauges measures the deformation of the instrumented body due to the force loading. The bipolar bridge voltage supply is ± 15 V. A PCB uniaxial accelerometer model 352C65 secured to the hand rest provides the acceleration that will be used to calculate the velocity.

The time varying force that a cyclist must apply on the brake hood to steer and accelerate the bike has a frequency content below 2 Hz. This force cannot be distinguished in the time domain from the force interaction between the brake hood and the hand resulting from the vibration caused by the road surface. Note in passing that a high pedaling cadence of 120 RPM corresponds to 2 Hz. In this study, it is assumed that the cyclist is leaning on the brake hood (not grasping it) and that the steering forces are small enough to be considered negligible for the purposes of this study. The frequency span considered in this study for all measurements is 3–100 Hz.

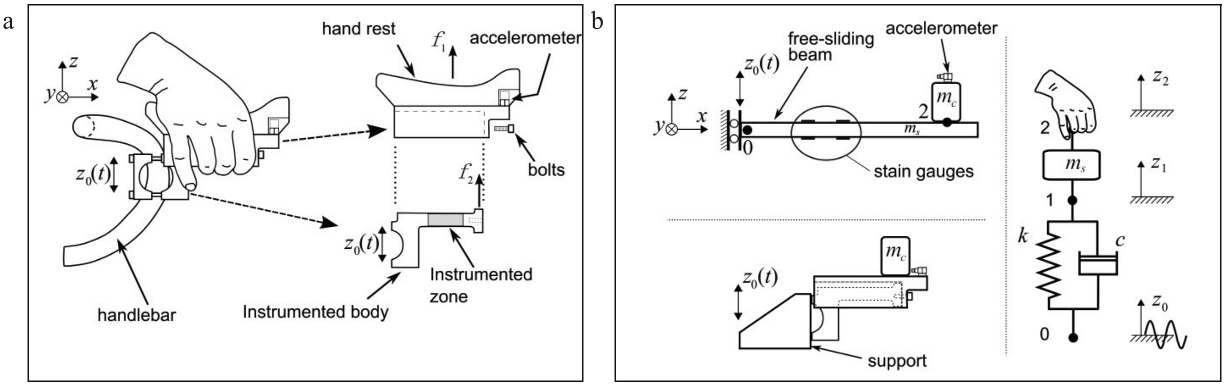

Fig. 1. (a) Brake hood force transducer; (b) one degree of freedom base excitation model for representing the dynamic behavior of the instrumented brake hood.

It is important to stress that the dynamic system studied is excited by the motion of the base $z_0(t)$ which corresponds to the motion of the attachment point of the instrumented brake hood to the handlebar.

All measurements were made using a LMS SCADAS recorder (model SCR01-08B) driven by LMS Test.Lab software. Dead weights have been used to statically calibrate the force transducer and also to evaluate its cross-sensitivity. The nominal z-axis sensitivity was determined to be equal to 12.3 μV/N.

4. Dynamic calibration of the power transducer

4.1. Dynamic brake hood calibration

The force transducer dynamic calibration technique used in this study is described in an ISO 2631-1 [7]. Note that both the calibration technique setup and the brake hood are base excited systems. A simplified equivalent representation of the instrumented brake hood is shown in Fig. 1b. A free-sliding beam equipped with strain gauges is set in motion by imposing a vertical displacement $z_0(t)$ at the left hand side of the beam. The numbers 0, 1 and 2 in Fig. 1b indicate the contact point locations between structures.

The base excitation corresponds to the movement of the handlebar at the brake hood attachment point. The suspended mass m_c used for the dynamic calibration is entrained by the beam applying a vertical force f_2 at point 2. The mass m_c mimics the mass of the hand. It is the reaction of the suspended mass being set in vibration that causes the force f_2. An accelerometer measures the acceleration of the mass m_c. A one degree of freedom model of the instrumented brake hood is shown in Fig. 1b. Both the beam and the instrumented hood have a stiffness k and a damping coefficient c. The mass m_s represents the seismic mass of the transducer which corresponds to a portion of the beam's mass at the right hand side of the strain gauges. It has been noted [6] that the stiffness of the instrumented hood must be as close as possible to the stiffness of a commercial brake hood to prevent any change to its dynamic behavior, even though the first natural frequency of the brake hood is close to or within the frequency range of interest. Note that if we were to manufacture a stiff transducer to push away the first bending mode frequency from the frequency zone of interest, this would constitute a design misconception for a base excitation system [8]. To achieve dynamic calibration, the instrumented brake hood is attached to a rigid support on top of a shaker table imposing a vertical sinusoidal oscillation as shown in Fig. 1b. Known masses m_c are attached in sequence on top of the hand rest. The voltage output V_f, provided by the strain gauges of the force transducer, is

$$V_f = S_f (m_s + m_c)\ddot{z}_2 \tag{3}$$

where S_f (μV/N) is the brake hood force sensitivity. The voltage output V_a of the accelerometer is

$$V_a = S_a \ddot{z}_2 \tag{4}$$

where S_a (mV/ms^{-2}) is the accelerometer sensitivity. A calibrated accelerometer with an accurate and known sensitivity must be used here because it will constitute the reference of the calibration process. Note that both the force and the acceleration will be used subsequently to determine the absorbed power. The ratio of Eqs. (3) and (4) provides the following expression:

$$\frac{V_f}{V_a} = \frac{S_f}{S_a}(m_s + m_c) \tag{5}$$

Using a sinusoidal signal to excite the brake hood, the Frequency Response Function (FRF) V_f / V_a can be measured at a specific frequencies between 3-100 Hz for different calibration masses m_c. Amplitudes and phases are measured. A total of 9 masses are used, ranging from 0.09 kg to 0.67 kg. At each frequency, a plot between V_f / V_a vs m_c can be obtained. The slope s of the straight line is equal to S_f / S_a . The force transducer sensitivity S_f can be calculated. According to Eq. (6), the horizontal axis intercept point provides the seismic mass $-m_s$. the following results are obtained for the brake hood force sensitivity and seismic mass: S_f = 11.92 μV/N and m_s = 0.198 kg.

4.2. Phase correction between the measured force and acceleration

To accurately measure the average absorbed power, both the amplitude and the phase accuracy between the force and the velocity signals must be verified. According to Eq. (1), any extraneous time delay between the force and the velocity that is not associated with the physical phenomenon being studied will bias the power measurement. Time delay is associated in the frequency domain to a phase error in the cross-spectrum of Eq. (2). The source of phase errors can be associated with signal conditioning or with the A/D process.

The dynamic calibration procedure of the force transducer described in section *4.1* enables us to measure amplitude ratios between the force and the acceleration but also provides phase relationships. After having determined the force transducer sensitivity, corrected the phase mismatch and adequately calculated the velocity, an accurate estimation of absorbed power is expected to be obtained using Eq. (2).

4.3. Calibration validity check using the Power Calibrator

In order to ascertain the accuracy of the measured absorbed power using the instrumented brake hood, a device herein referred to as the *Power Calibrator* was developed to impose a load that can dissipate energy as well as measure the absorbed power using its own independent transducer. Fig. 2a shows the Power Calibrator made of a wood handle equipped with a piezoelectric PCB head impedance model 288D01 providing force and acceleration signals. Only axial forces can be applied to a piezoelectric force transducer to accurately measure the force. A sharp contact pin is fixed at the free end of the impedance head to prevent any application of cross loads.

To use the Power Calibrator, a full bike is first installed on a road simulator [9]. Two hydraulic shakers impose a vertical displacement under each wheel. The bike is held in a vertical position with the help of horizontal bungee cords attached to the seat tube. A 0-100 Hz random signal is use to drive the shakers.

While the bike is being excited and as shown in Fig. 2a, the Power Calibrator is positioned over the brake hood to impose a downward DC force. The Power Calibrator is set in motion by the brake hood vibration with the vibrating hand absorbing energy. The impedance transducer provides the signals to measure the absorbed power. The same filters, signals treatment, phase correction and numerical calculation steps described previously are used with the impedance head signals to calculate the power using Eq. (2). Fig. 2b allows the power measured by the brake hood transducer and the Power Calibrator to be compared. The level of correspondence is excellent. The discrepancy between the total power of each is 0.02 W or 3%.

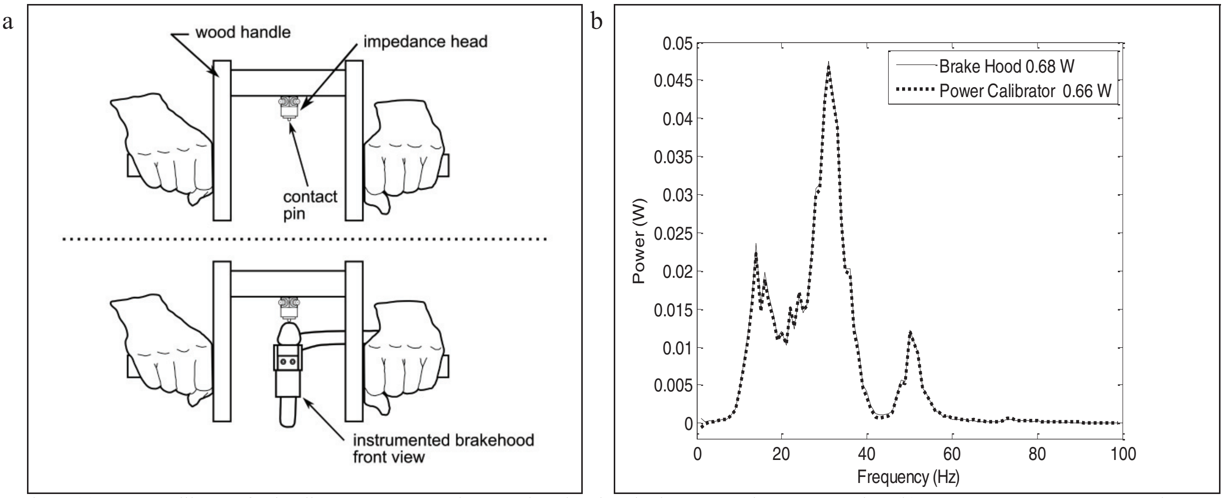

Fig. 2.(a) Power calibrator for loading a structure and measuring the absorbed power at the contact point. (b) Power measurement comparison between the instrumented hood and the Power Calibrator.

4.4. Power measurement on the road

In order to provide in-situ measurement of the power absorbed at one of the cyclist's hands, the instrumented brake hood was installed on a road bike. A coarse granular road was selected for the test and the bike speed was kept constant at a speed of 26 km/h. The solid line of Fig. 3 shows a typical measured average frequency spectrum which a total absorbed power measure by the brake hood of 0.99 W.

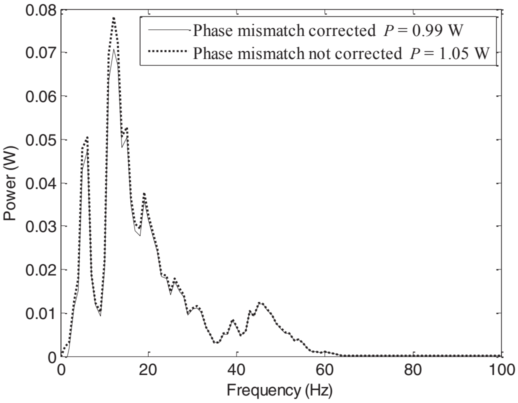

Fig. 3.Power measurement on a granular road at the cyclist's hand (right hand only). Comparison of power spectra with and without correction for the phase mismatch.

5. Discussion

Calculating the absorbed power in both the time and frequency domains according to Eq. (1) and Eq. (2), respectively, should provide the same results. However, the difficulty in obtaining the numerical velocity from the acceleration in the time domain must not be underestimated. A simple "detrending" of the time signal is not sufficient in some cases, especially for non-stationary signals.

The in-situ measurement spectrum of Fig. 3 shows that in the case of the cyclist's hand, the absorbed power is at a relatively low frequency. To illustrate the importance of correcting for the phase mismatch, the phase mismatch correction was eliminated in the power calculation. The spectra are compared in Fig. 3. A 6% variation between the total power of each curve is noticed. To obtain accurate measurements if the absorbed power is at low frequencies, a phase mismatch correction is recommended.

Implementing a phase correction in the time domain is a complex task. In the frequency domain, correcting the phase is straightforward and simply requires subtracting the phase amplitudes from the acceleration phase (relative to the force). Integrating the acceleration to get the velocity is also straightforward and requires only dividing the complex acceleration spectrum by $j\omega$. An average cross-spectrum calculated over several time segments allows the non-correlated noise between the force and the velocity to be eliminated. This is an advantage of using the power as a metric rather than acceleration, because averaging the signal does not eliminate the noise in the acceleration signal. Moreover, in the frequency domain, the coherence function between the force and the acceleration is easily calculated. The coherence provides valuable information on the quality of the signals and on the number of averages required to eliminate the noise in the power measurement. For all these reasons, we strongly recommend calculating the power in the frequency domain.

6. Conclusion

The objective of this study was to obtain a dynamic calibration of an instrumented brake hood transducer to measure the power absorbed at one of the cyclist's hands. A calibration technique using suspended masses and a base excitation was used to obtain the sensitivity of the force transducer as a function of the frequency as well as to obtain the phase mismatch between the acceleration and force signals. The force transducer's seismic mass was also measured. Its sensitivity did not show any strong frequency dependence. The phase mismatch is prevalent mainly at low frequencies. Because the energy dissipated at the cyclist's hands is also at low frequency, a phase correction is used to maximize measurement accuracy. A Power Calibrator was introduced and was used to assess the accuracy of the power measurement provided by the instrumented brake hood. Similar to a commercial calibration apparatus such as an accelerometer or a microphone calibrator, the Power Calibrator is an easy to use device that verifies the proper functioning of the instrumented brake hood for power measurements. The advantages of using the frequency domain rather than the time domain for processing and calculating the power were presented and discussed.

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