Dynamic calibration of a strain gauge based handlebar force sensor for cycling purposes

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Abstract

Dynamic measurements on bicycles are implemented for assessing the vibration comfort of the cyclist or for the measuring the load distribution at bicycle components. Accelerometers are typically used for comfort evaluation, force sensors are selected for comfort and load measurements. For cycling purposes, typically custom made, strain gauge based, are designed. These sensors are implemented for static and dynamic load measurements. When force transducers are used for dynamic measurements, it is important to have detailed knowledge of the dynamic properties of the force transducer and the corresponding electronic measuring equipment, as considerable errors can occur under dynamic conditions. Moreover, the arrangement of the force transducer, the mounting conditions and the whole mechanical structure of the measuring arrangement may significantly influence the uncertainty of dynamic force measurement. This is investigated for a strain gauge based handlebar force sensor. The dynamic calibration procedure assesses the amplitude sensitivity, the phase response and the seismic mass. It is observed that (i) in-situ boundary conditions significantly reduce the expected behavior calculated from idealized clamped boundary conditions and (ii) the dynamic force sensor properties are different from the DC properties. As a result from the dynamic calibration procedure, the developed handlebar force sensor can be used in the frequency range from DC to 35 Hz.

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1. Introduction

Accelerometer measurements are commonly used to understand the dynamic behavior of a vibrating system. It is a quick and relatively easy method to detect resonance frequencies, mode shapes and even the damping of a system. However, some applications require additional measuring techniques for a better comprehension of the system dynamics. For example, force sensors can measure the (dynamic) interaction between two elements in a system. This is particularly interesting for the bicycle-rider interaction characterization. Acceleration measurements at the contact points do not perfectly grasp the bicycle-cyclist interaction. When the cyclist firmly grips the handlebar, the acceleration level will decrease but the cyclist imposes higher contact forces. This analysis requires the design of force sensors to measure the bicycle-rider interaction at the contact points.

Force sensors for cycling purposes were initially used for static force measurements [1-3] but the design evolved towards dynamic force measurements for characterizing the frame loads and vibration characterization for in-situ loading conditions [4-8]. Nevertheless, the functioning of custom made force sensors for vibration analysis during cycling has not been reported before. The design and calibration of force sensors for dynamic measurements shows much more complexity than designing strain gauge based force sensors for quasi static measurements (< 5 Hz loading frequency).

The measuring principle of strain gauge based force sensors is equivalent with a cantilever beam configuration [9]. In the cantilever beam configuration with a force applied at the free end of the beam, the longitudinal strain linearly increases from the free end to the clamped end of the beam. In other words, the strain gradient is constant over the length of the beam. This is only valid for the static beam deformation. When a force sensor is used for measuring dynamic loads, the effect of the sensor’s vibration behavior on the measurement must be considered. This is of particular importance with custom made strain gauge based transducers. The force sensor is a structural component of the bicycle, which means that the dynamics of that component potentially sway the measurement accuracy of the dynamic force measurement. With a harmonic excitation force, the beam deformation is determined by the mode shapes of the beam. Consequently, the strain gradient is not constant anymore but the strain gradient varies along the length of the beam. This requires a thorough understanding of the sensor dynamics, as explained in the next sections.

2. Design requirements for dynamic force measurements

When measuring the bicycle-rider interaction due to road excitations, the cyclist is considered as a suspended mass leaning on the bicycle. This is referred to as a base excitation configuration, when the structure’s response is due to the displacement excitation at the structure. Drouet [10] performed a numerical study on the influence of the suspended mass and the system damping on the measuring accuracy of the strain gauge based sensor in a cantilever beam configuration with base excitation. An essential requirement is that the first mode shape must be pure in-plane bending, the cantilever beam must be as light as possible and large material damping is preferred.

Based on these advised, a carbon fiber reinforced composite tube with a circular cross section is selected. The diameter is 32 mm and the thickness is 2 mm. The handlebar is assembled from two pieces of 235 mm which are glued to each other. Both tube ends are glued to a solid aluminum connection piece. This meets the requirement to use a solid connection piece to reduce the stress concentrations at the center of the handlebar [9]. Curved ends, as with a normal racing bicycle handlebar, are omitted because these eccentric masses would result in combined bending and torsion for the first mode shape. The result is depicted in Fig. 1.
3. Dynamic calibration

When force transducers are used for dynamic measurements, it is important to have detailed knowledge of the dynamic properties of the force transducer and the corresponding electronic measuring equipment, as considerable errors of several percent can occur under dynamic conditions [11]. Moreover, in special applications the arrangement of the force transducer, the mounting conditions and the whole mechanical structure of the measuring arrangement may significantly influence the uncertainty of dynamic force measurement [12]. The deviation increases with increasing frequency and mainly depends on the stiffness and the mass distribution. In addition to the resonance behavior of the force transducer, the resonance behavior of the surrounding mechanical structure can significantly influence the measurement results.

This section presents the setup of a dynamic testing facility for the handlebar force sensor. The results can be used to compensate and estimate the errors of dynamic force measurement. In essence, the relationship between the output voltage from the Wheatstone bridge and the applied force must be assessed. This sensor calibration procedure assesses the amplitude sensitivity, the phase response and the seismic mass as function of the excitation frequency (from 5 Hz to 100 Hz) [13-16].

The calibration method is assumed for a cantilever beam configuration. But the stem, which holds the handlebar at the center, is not a rigid fixture and fully clamped boundary conditions cannot be realized either. Therefore, two different boundary conditions for the clamping mechanism of the handlebar are considered. In the first configuration the handlebar is rigidly clamped at the center (Fig. 2a), whereas in the second configuration the handlebar is held by the stem (Fig. 2b). The influence of an additional mass $M'$, located at the opposite side of the handlebar, on the dynamic sensitivity is also investigated (cf. Fig. 2a and Fig. 2b). This analysis is useful since the handlebar is always held by two hands, cf. two suspended masses, during cycling.

![Fig. 1 Handlebar design for dynamic force measurements: full overview with nomenclature](image)

![Fig. 2 Clamped boundary conditions for the handlebar: (a) rigid clamping mechanism at the centre of the handlebar, (b) in-situ boundary](image)
conditions with handlebar assembled to the stem.

The discussion on the results from both test configurations is given for the vertical force component at the left hand side of the handlebar only. The results from the other measuring directions are similar. The base excitation is a white noise signal with a root mean square (r.m.s.) level of 0.55 g in the frequency range 5-100 Hz. Seven calibration masses $M$ are available: 0.7176 kg, 0.8900 kg, 1.0694 kg, 1.4283 kg, 1.7946 kg, 2.1332 kg and 2.4920 kg. The reference accelerometer has a calibrated sensitivity of $S_A = 99.1$ mV/g. The output voltage from the two Wheatstone bridges at one side of the handlebar is also measured. The voltage level from the orthogonal force component will be compared with the reference voltage signal $v_F$ for cross axis sensitivity. All signals are sampled with a sample frequency of 2048 Hz, the frequency response spectra $v_F/v_A$ are calculated for a frequency resolution of 1 Hz and a Hanning window with 67% overlap is used to reduce leakage errors.

First, the test configuration with the firmly clamped handlebar is discussed (Fig. 2a). The dynamic sensitivity curve is measured for three different masses $M'$, the result is depicted in Fig. 3a. It is noticed that the sensitivity value is not constant in the considered frequency range. This non-constant sensitivity is rarely seen with commercial force sensors, though this does not prevent to calculate the correct force amplitude. The curve with the largest additional mass $M'$ slightly deviates from the other curves near 80 Hz. This is probably due to a resonance frequency at 80 Hz at the handlebar side where this additional mass is connected. In conclusion, the result from this calibration procedure is reasonably good.

Second, the test configuration with the handlebar fixed to the stem is investigated (Fig. 2b). The sensitivity curves are depicted in Fig. 3b. The calibration curve with $M' = 0$ kg approximately matches with the corresponding curve in Fig. 3a. The curve is free of fluctuations from resonances. This is in contrast with the calibration curves if an additional mass is added to the opposite side of the handlebar. The presence of resonance frequencies is dominantly present and more pronounced. This indicates that the stiffness of the boundary conditions significantly affects the force sensor dynamic response. The frequency range from DC to 35 Hz is free of resonances, as visualized in Fig. 3b.

![Dynamic sensitivity handlebar force sensor](image)

**Fig. 3** Dynamic sensitivity curves: (a) with firm grip system at the centre of the handlebar, (b) with handlebar clamped to the stem.

Besides the sensitivity of the force sensor, the phase response is also of particular importance. The phase lag between the force and acceleration is theoretically zero in this base excitation calibration test procedure. However, the signal from the acceleration sensors inherently has a phase delay which is due to the integrated high pass filter in the data acquisition hardware for integrated electronic piezo-electric (IEPE) signal processing. This phase lag between the force and acceleration is depicted in Fig. 4a for the frequency 5-50 Hz. The phase fluctuations reflect the results from the sensitivity curves, only excitation frequencies below 35 Hz have satisfactory phase response.

A force sensor is also characterized by its seismic mass. The seismic mass can also be derived from the calibration test procedure. The experimental result for the handlebar force sensor is depicted in Fig. 4b. The seismic mass slightly oscillates at low frequencies but exponentially increases near the resonance frequencies.
It is also important to verify the cross-axis force sensitivity. With a vertical base excitation, it is expected that the horizontal force amplitude equals zero. In practice this is not feasible because of minor misalignment of the strain gauges and effects from non-ideal boundary conditions which possibly introduces out-of-plane handlebar bending. This is verified by comparing the r.m.s. amplitude of the orthogonal force components. The frequency response function from the vertical to horizontal force ratio is calculated. This is depicted in Fig. 5 for $M' = 1.4283$ kg. The vertical force amplitude is on average 8.5 dB higher than the horizontal force amplitude. Hence, the vertical base excitation vibration contributes approximately 14% to the horizontal force measurement.

4. Conclusion

A strain gauge based handlebar force sensors in a cantilever beam configuration is implemented for dynamic load measurements in cycling. The handlebar is designed to measure the vertical and horizontal force at the left and right hand side. The handlebar design is a carbon composite tube which is clamped at the stem. This geometry is different from a normal racing bicycle handlebar design, though it is useful to assess the vibration isolation properties of many bicycle components (wheels, frames and front forks), except for the handlebar.

The dynamic calibration procedure highlighted some relevant findings which should be considered. The dynamic behavior of the handlebar shows no significant fluctuations when the handlebar is firmly clamped at the center. However, when these theoretical boundary conditions are not fulfilled, large variations from the expected value are observed. This is seen when the handlebar is gripped by the stem of the bicycle, representing in-situ boundary conditions. The dynamic response of this component significantly disturbs the vibration properties of the handlebar.
force sensor. The frequency range is limited to 35 Hz instead of the proposed 100 Hz. Hence, it is necessary to calibrate the force sensor with in-situ boundary conditions rather than using idealized boundary conditions. It is the best representation of the sensor functionality when finally assembled in the system (cf. the bicycle). The downside is that the accuracy of the force sensor might reduce and extensive signal post-processing is necessary.

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