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Measurement and analysis system for bicycle field test studies

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Abstract

The work presented describes the development of a measurement and analysis system for bicycle field test studies capable of measuring structural responses including strain and acceleration. The system incorporates 24 sensors measuring strain, 4 sensors measuring acceleration, a stand-alone data acquisition unit weighing 1.7kg which can be mounted behind the seat post and an offline programme analysing the data obtained. The system has been fully implemented on a BMX bicycle for the work presented herein. Piezo-electric accelerometers and resistance strain gauges are used as sensors which are wired to the data acquisition (DAQ) unit. The DAQ unit consists of a controller-chassis, 4 signal conditioning modules and specific application software. The software which controls the measurement process performs sensor calibration, simultaneous 24 bit data acquisition with a sampling frequency of 1000Hz, signal conditioning and data storage. The sampling frequency was established as optimal in specifically designed assessment tests. The data is post-processed to determine the frequency responses, maximum accelerations and strains and to illustrate the time behaviour of accelerations and strains. The measurement and analysis system is validated in common cycling scenarios and a race simulation on a race track. The system is applicable to different types of bicycles and enables comprehensive investigations of structural phenomena.

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1. Introduction

To improve the engineering design of a bicycle it is necessary to thoroughly understand the complex load cases to which it is subjected to. The bicycle is constantly subjected to loads from the riding surface (at the wheels) and the rider at three potential points of contact (the handlebars, the pedals and the seat). Measuring the structural responses of a bicycle in a realistic field test is the only certain method of obtaining actual data on what a bicycle is subjected to under use and abuse scenarios. To achieve this, a measurement system is required capable of acquiring structural responses during cycling.

The aim of the work presented was the development and validation of such a measurement and analysis system. While this is not the first attempt to develop such a system, it has been done in a more systematic way and with more attention to detail than other systems presented within the literature.

The outcome of this work is a low weight, flexible, stand-alone measurement and analysis system enabling the acquisition of a comprehensive amount of data on the structural responses of strain and acceleration with signal acquisition properties determined to be optimal for realistic cycling conditions.

2. Current state of art

There exist a number of studies describing the development of some form of measurement system for bicycle field test studies. Publications have been found describing the use of a measurement system in field test studies with mountain bicycles (e.g. Champoux et al. (2004), De Lorenzo and Hull (1999)), road bicycles (e.g. Bluemel et al., (2007)) and even foldable city bicycles (Pirnat et al. (2011)). Many studies stored the data acquisition (DAQ) unit in a backpack; others mounted the system directly to the bicycle. Except that by Barski et al. (1995), no research aiming at acquisition of structural responses implemented wireless signal transmission. The signal acquisition in Barski et al. (1995) is limited to eight channels without providing information about the sampling frequency used.

From the literature, some observations regarding measurement systems used can be made. Considering the sampling frequency, the arguably most important signal acquisition property, a range of 200-2500Hz has typically been used. This demonstrates a degree of uncertainty about what is considered an optimal sampling frequency. This is crucial as it indicates that research may have been impeded by a loss in information (sample frequency too low), or an overwhelming amount of data and a degree of introduced noise in the signal (oversampling).

The systems previously used provided ADC resolution in a range of 8-24bit and anywhere from 4 to 32 measurement channels were implemented in measurement systems depending on the aim of the research. Considering the literature, a measurement system incorporating at least 20 channels could be considered as comprehensive. For such systems, the lowest weight documented is found in Bluemel et al. (2007) with 3kg for a 23 channel measurement system. The lowest mass of 1.2kg is mentioned in Drouet et al. (2009) for a measurement system offering only four channels to measure loads on the pedals.

Regarding the physical quantities acquired, most studies measured forces at points close to load inputs (e.g. handlebars, stem, pedals and hubs); however, almost no information is available regarding strains and deformations on the frame. Moreover, within the literature, studies measuring loads did not measure accelerations and vice versa; except of Barski (1995) who; however, does not provide information on accelerations measured. This is significant, as it means that the connection between the external dynamic inputs from the rider and environment and the strains experienced by the frame is not well understood.

3. Measurement system definition

The development of the measurement and analysis system was based on requirements defined following the outcome of specifically designed assessment tests to determine what constitutes an optimal acquisition of signals of structural responses on bicycles in field test studies, as well as information provided within the literature regarding the state-of-the-art for such systems. In addition, the system developed should be easily configurable and applicable to any type of bicycle.
3.1. Assessment tests

The assessment test series was carried out to determine the sampling frequency required to optimally acquire the analogue strain and acceleration signals during in-field bicycle testing. Moreover, it was intended to obtain information about suitable sensor locations on the bicycle for the final setup of the measurement and analysis system.

For the test series, a road-racing bicycle was used due to its high stiffness, low weight, and low volume high-pressure tires. This combination of properties was considered less likely to damp out any vibrational phenomena of interest. A four channel data acquisition system already in service, but not specifically designed for this purpose was used to perform the assessment test series. As with studies in the literature, the DAQ module and a laptop running software for the DAQ system were stored in a backpack during the tests. Four piezo-electric accelerometers were mounted on the bicycle (dropouts, seat clamp and under the saddle).

To obtain results applicable to all cycling situations, test scenarios representing continuous excitation of the bicycle (“riding over a smooth tar surface”, “riding coarse tar surface”) and single event load input scenarios (“riding over a traffic bump”, “riding head on against a kerbside”) were investigated. Measurements for the first three scenarios were done at 25-30km/h, whereas the scenario “riding head on against a kerbside” was performed at a speed of 10-12km/h.

Due to the uncertainty and lack of knowledge within the literature regarding the exact frequency content of vibration phenomena on bicycles in use, the assessment tests have been performed by intentionally oversampling using a sampling frequency of 10,000Hz. Once data was acquired from all test scenarios, it was analysed in a MATLAB program down-sampling the signals to simulate frequencies of 100Hz, 200Hz, 500Hz, 1000Hz and 2000Hz. The program then plotted the acceleration signals for each sampling frequency and determined the frequency content by calculating the response spectra implementing a Fast Fourier Transform (FFT). In the next step, the frequency spectra and the acceleration profiles of the differently sampled signals were compared.

Figure 1 and 2 illustrate the comparisons made for signals obtained on the dropouts of the bicycle. With regards to the frequency spectra, it was found that the lower frequencies (100Hz, 200Hz) give clearly a poorer representation. The sampling frequencies 10000Hz, 2000Hz and 1000Hz show an almost identical frequency spectrum, whereas slight differences can be noted for 500Hz. Moreover, it was determined by comparing the acceleration profiles that frequencies below 1000Hz tend to clip peaks in acceleration. Comparing these signals in
such a way yielded significant insight which was not presented within the literature. From the evidence presented, a sample frequency of 1000Hz was determined to optimally acquire the signals.

The single input scenarios were also filmed with consumer grade high-speed camera (600 frames per second) providing information about possible high deformation areas on the bicycle. Such information was used determining locations for the application of strain gauges for the final test set-up.

3.2. Development of the measurement and analysis system

As an outcome of the assessment test series and from information provided within the literature the following requirements for a suitable measurement system were defined:

• record data from strain gauges and accelerometers simultaneously at 1000Hz,
• have a minimum of 12 bit ADC resolution and record at least 20 channels of sensor input simultaneously,
• able to run as a stand-alone device and store data of at least an hour for in-field testing,
• have as low mass as possible; a weight of two filled up water bottles (ca. 1200-1300g) is desired,
• be easily configurable for multiple bicycle types.

The intention of this work was to develop the measurement and analysis system based on commercially available technology rather than designing and manufacturing complicated electronic hardware.

Evaluating commercially available hardware, it was found out that wireless systems cannot presently fulfil the requirements defined regarding the amount of channels and a simultaneous acquisition with 1000Hz due to limitations in bandwidth. Wired systems, while generally more sophisticated with regards to measurement capabilities, struggle to fulfil the requirements for weight.

The National Instruments controller-chassis NI cRIO 9076 was chosen as the DAQ unit. The cRIO 9076 contains four slots for signal processing modules, an onboard processor and built-in storage capacity. Modules for strain (NI 9235) and acceleration (NI 9234) measurements were used resulting in 28 measurement channels (24 for strain, 4 for acceleration). The modules for strain measurements provide a built-in quarter-bridge completion circuit. Other modules can be used to enable acquisition of alternative types of sensors such as analogue voltages from displacement transducers. The modules allow sampling up to frequencies of 10kHz for strain and 51.2kHz for acceleration. In this configuration the DAQ unit weighs 1300g. The power supply of the system was ensured by a battery pack enabling the system to run for 4.5h and weighing 400g which results in a total weight of the measurement and analysis system of 1700g. To enable an easy application to various bicycle types, minimise the interaction with the rider and to allow sensor applications along the frame the DAQ unit was fixed to a seat post mounted carrier (350g) behind the saddle. The final set-up of the measurement and analysis system on a test bicycle is shown in figure 3.

Uni-axial piezo-electric accelerometers (PCB Piezotronics 352C65) with a range of ±50g and strain gauges (Vishay Micro-Measurements & SR-4, area of measurement: 2x6 mm) with a nominal resistance of 120Ω were used as sensors. The sensor locations, shown in figure 3, were chosen based on observations made in the assessment test series and to obtain a general overview of strain generated along the frame in cycling. Hence, focus was put on the high deformation area at the area of the down tube and top tube close to the joint with the head tube. Three strain gauges were applied aligned to each other on the bottom side of the down tube allowing detailed information on strain generated in this area. A total of 9 strain gauges were applied to the down tube, 4 to the top tube, 3 to the handlebars, the chain stays, the seat stays and 2 to the fork. Accelerometers were mounted with a cyanoacrylate adhesive to the load input locations on the bicycle (both dropouts) and on top of the frame at the stem and the seat clamp.
Application software (LabVIEW FPGA realtime project) was developed to use the cRIO 9076 as a stand-alone system and to enable a signal acquisition as required. The software was written to perform the simultaneous acquisition of 28 channels of analogue signals from strain gauges and accelerometers at 1000Hz, and calculate the strains and accelerations for the respective channel. It also performs an initial system calibration, applies signal conditioning procedure to the measurement signals, such as zero-offset calculation and error-factor calculation, and stores the data on the chassis. The system also allows the execution of multiple tests in a row without the need to download the data. In its current configuration, the system is capable of acquiring data for a maximum of 101min.

After testing, data is downloaded from the chassis and specific steps of post-processing are performed using a MATLAB script. The script processes the data to determine the maximum accelerations, applies a 4th-order Butterworth filter with a cut-off frequency of 250Hz and performs a FFT of the acceleration signals to calculate the response spectra. This provides information about the frequency content of the acceleration signals and the severity of vibrations at the various measurement points. Furthermore, the time behaviour of the accelerations and the strains are plotted providing insight into the interaction of these structural responses. Maximum values of strain are determined for each sensor indicating high strain areas and possible weak points. The strains of all measurement points are captured for the event of the maximum strain generated on the frame during a test ride.

4. Application of the system

A comparative study of accelerations and frequency responses on a road bicycle, a mountain bicycle and a BMX racing bicycle was performed with the system. As an outcome, comparisons between the different bicycle types on the maximum accelerations occurring and the vibrational phenomena were made. Moreover, a comprehensive study of the structural responses strain and acceleration was carried out with a BMX racing bicycle. Detailed information about strains generated along the frame was obtained and the interdependency of acceleration and strain was proven by the data acquired.

Figures 4 and 5 give an example of the results obtained for a jump off a kerb with a BMX bicycle. In figure 4, the interdependency of accelerations and strains is illustrated by the strains measured on fork and handlebars following the impact of the bicycle on the surface indicated by a sharp peak in acceleration at 4.14s. In figure 5, high strains close to the joint of top tube and down tube with the head tube following the impact of both wheels on the surface are displayed. Detailed findings of the studies are described in Koellner et al. (2014).
Figure 4: Accelerations measured on the front dropout and handlebar and strains measured on fork and handlebar during a jump off a kerb

Figure 5: All accelerations measured and strains measured on sensor locations on top tube and down tube

5. Discussion

The measurement and analysis system developed enables a comprehensive and high-quality data acquisition of structural responses on bicycles. It is the first system, within the public domain, which applies specifically defined optimal signal acquisition features for strain and acceleration measurements in bicycle field test studies. The desired weight for the measurement system could not be met. The DAQ unit alone weighs exactly as much as intended (1300g, the weight of two filled up water bottles). It has to be considered that the location of the system is on a different part of the bicycle. With optimisations of the power supply and the application to the bicycle it should be possible to decrease the total mass of the system. The system is robust proven by its application to race simulations on a BMX race track.

6. Conclusion

The measurement and analysis system developed is a powerful tool for studying structural responses on bicycles in field test studies. By systematically developing the system based on engineering insight, the capabilities of the system are optimized for this application. Comprehensive data on structural responses can be obtained providing essential insight aiming an optimization of the engineering design of bicycles.

References