Bicycle Structural Dynamics

Y. Champoux, S. Richard and **J.-M. Drouet,** VélUS, Université de Sherbrooke, Sherbrooke, Québec, Canada

The joy of riding a bicycle is enhanced with the advent of new materials, the development of new technologies and design procedures that improve comfort and durability. This article looks at the commitment of the research group VélUS to help the industry keep developing this incomparable machine by studying its dynamic behavior.

A bicycle is a transport vehicle with unsurpassed efficiency and among the most used on the planet. Several million new bikes are sold each year, and this generates an important commercial activity. As shown in Figure 1, a bike is a surprisingly simple structure made of a frame built from a few tubes assembled to create two triangles on which several components are attached. This simple structure allows custom frame builders to make a living with an annual production of a few hundred bikes as well as allowing large companies to sell millions of bikes a year. Cost and marketing are obviously key factors in the business. On the technical side, the weight, stiffness and comfort of a bike are three important characteristics that still drive most new developments Steel, titanium and aluminum are materials still used in the industry but carbon fiber is becoming the most popular material for frames and for almost all bike components.

A bicycle is a light structure that has to support a much heavier weight (the cyclist). The components and the frame are subjected to time-varying force excitations imposed by the cyclist and by the road. Its dynamic behavior becomes an important issue, because it is directly linked to the bike lifetime, maneuverability, efficiency and comfort. Few studies have addressed the dynamic behavior of a bike in real operating conditions, and one reason is linked to rider influence. Not surprisingly, the coupling between a bike and a rider completely modifies the dynamic behavior of a bike. One has to simply consider that a bike exhibits lightly damped modes when tested in a free-free condition and highly damped modes when the bike is resting on a surface with the presence of a rider. The rider becomes part of the structure and introduces experimental difficulties and fuzziness to the results.

The more manufacturers can learn and understand about the dynamic response of their products, the more they will be able to benefit both current and potential riders.

Researchers at the Université de Sherbrooke research group VélUS have taken up the challenge in collaboration with the industry to develop know-how and knowledge in bicycle dynamics. The importance of teamwork, intellectual honesty and openness are essential ingredients in any relationship. The VélUS mechanical engineers, with expertise in modal analysis, metrology, material strength and biomechanics, joined their efforts to address these challenges. Other objectives of VélUS are to characterize perceptions, demystify wrong beliefs and to foster technology transfer to manufacturers. The mission of VélUS is to be recognized by researchers, people involved in the world of bicycling and by manufacturers to be an exceptional partner in knowledge development and in technology transfer.

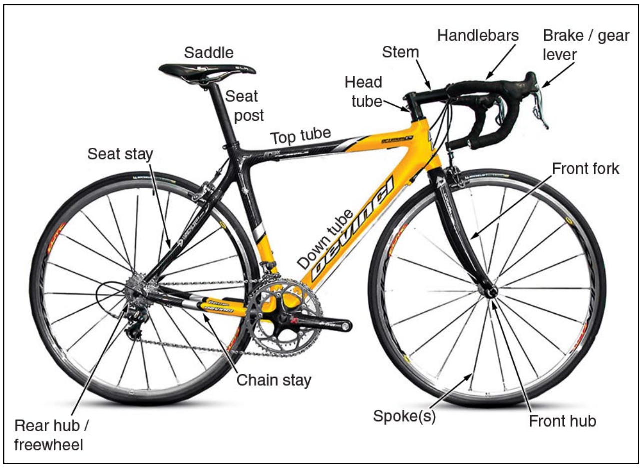

Figure 1. Bike frame and components.

Figure 2. Setup for SIMO and MIMO analyses.

Dynamic Analysis of Frames and Components

To get a good idea of the dynamic behavior of a bicycle structure, experimental modal analysis (EMA) can be used while considering different operating conditions in the lab with or without a cyclist or on the road. EMA allows input forces, natural frequencies, modal damping and scaled modal shapes to be obtained. SIMO (single input multiple output) and MIMO (multiple input multiple output) analyses were carried out using one or several shaker configurations. For SIMO, a single shaker is connected to the front wheel axle imposing forces in-plane and out-of-plane directions. For the MIMO configuration, an additional shaker is installed on the handlebars as shown in Figure 2.

Experimental Setup. For a better understanding of how the presence of a cyclist influences a bike's dynamic behavior, tests were conducted with and without the cyclist and the bike resting on a flat surface. Figure 2 shows the general arrangement of

Figure 3. Shaker 1 imposing horizontal force at 30° off bike plane.

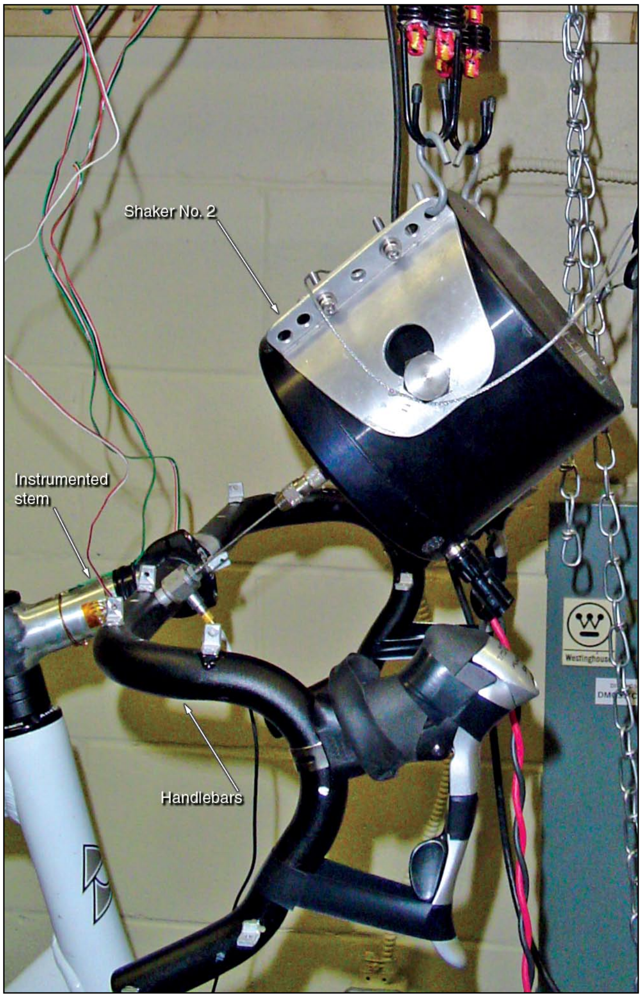

Figure 4. Shaker 2 mounted on handlebars.

the experimental setup. The bike is resting on a steel table and is held vertically with a set of soft elastic bands. The stiffness of the bands is selected to adequately support a 160-lb rider resting statically on the bike.

In SIMO testing, only shaker 1 is used. This shaker is a 50 force-lb shaker from MB Dynamics. The excitation is located on the front axle, and the horizontal force is oriented with an angle of 30° relative to the plane of the bike (see **Figure** 3). Shaker 2 (Brüel & Kjær, Type 4809) is installed on the handlebars to carry out the MIMO analysis, as shown in **Figure** 4. The handlebars proved to be a good location to input energy to the structure due to the damping caused by the presence of the rider's hands.[1] Random excitation (bandwidth 10-810 Hz) is used for both SIMO and MIMO analyses. A lower-limit frequency of 10 Hz is selected to avoid DC components in the force signal causing undesirable displacement of the bike. For testing with a cyclist on the bike, an instrumented stem is used to measure the force applied to the handlebars by the rider. The rider is asked to keep a constant 'natural' DC force applied to the handle bar throughout the tests. This cyclist attitude control is essential to maximize the reproducibility and to make the system time invariant.

Structural response was measured using a PCB triaxial accelerometer at 69 locations throughout the entire bike. This experimental setup also included measurements on both wheels at eight measurement points located on each tire rim.

Shaker control and data acquisition are performed using Brüel & Kjær PULSE™ system, and the modal parameters are extracted with Vibrant Technology ME'scopeVES software using a polynomial curve-fitting algorithm.

Modal Test Results Without Cyclist. **Table** 1 presents the results and a brief description for each mode of the SIMO test without a cyclist. **Figure** 5 shows three out the seven modes identified. The first mode is associated with the front and back movement of the front wheel, the fork horizontal stiffness being much lower than the stiffness of other parts of the bike. Without a rider, the damping ratios of all measured modes are about 2%.

Modal Test Results With Cyclist. Both SIMO and MIMO tests have been used for modal analysis when a cyclist is on the bike. The hands of the cyclist have a drastic effect on the bike's behavior due to energy transfer to the hands. A second shaker is then required to adequately disperse the excitation energy and to reduce nonlinear effects. The second reference provided by the additional shaker is also useful for identifying complex and local modes. **Table** 2 shows the modal parameters obtained in SIMO and MIMO configurations with a cyclist.

The results of the tests with a cyclist show that both SIMO and MIMO analyses give similar results for natural frequencies and mode shapes. However, damping ratios vary according to the technique employed. Also, the MIMO technique can extract one more mode than SIMO analysis (Mode 3). This can be explained by the fact that the there is a node of that mode at the reference location for the SIMO test (location of Shaker 1).

A comparison of **Table**s 1 and 2 shows that, as expected, the biker has a strong influence on the dynamics of a bike and almost all the modal parameters are modified. With a biker, there are only few

Table 1. Modal parameters from the SIMO test without cyclist.

Mode	Frequency, Hz	Damping, %	Mode shape description
1	24.0	1.54	Vertical motion of bike (no deformation) Front-to-back motion of fork
2	27.2	1.79	Steering tube torsion
3	33.5	1.67	Front-to-back motion of fork
4	39.8	1.28	Frame first bending mode
5	44.0	0.45	Stem torsion mode
6	54.3	0.93	Stem bending mode
7	67.5	0.27	Front-to-back motion of handlebars

Table 2. Modal parameters from the SIMO and MIMO tests with cyclist.

Mode	Frequency, Hz SIMO	(Damping, %) MIMO	Description
1	27.6 (5.3)	27.8 (7.1)	Front-to-back motion of fork
2	49.4 (4.5)	48.9 (5.8)	Frame torsion, lateral motion of fork and front wheel first bending mode
3	–	87.5 (1.6)	Stem torsion and front wheel second bending mode
4	148.0 (1.1)	148.0 (0.9)	Lateral motion of fork and front wheel third bending mode
5	173.0 (3.27)	174.0 (2.6)	Lateral motion of the handlebar tips and 3D fork motion
6	243.0 (0.7)	243.0 (0.7)	Fork and handlebars tips lateral motion and front wheel fourth bending mode
7	291.0 (0.5)	290.0 (0.7)	Lateral motion of fork and first bending mode for top tube and seat stay

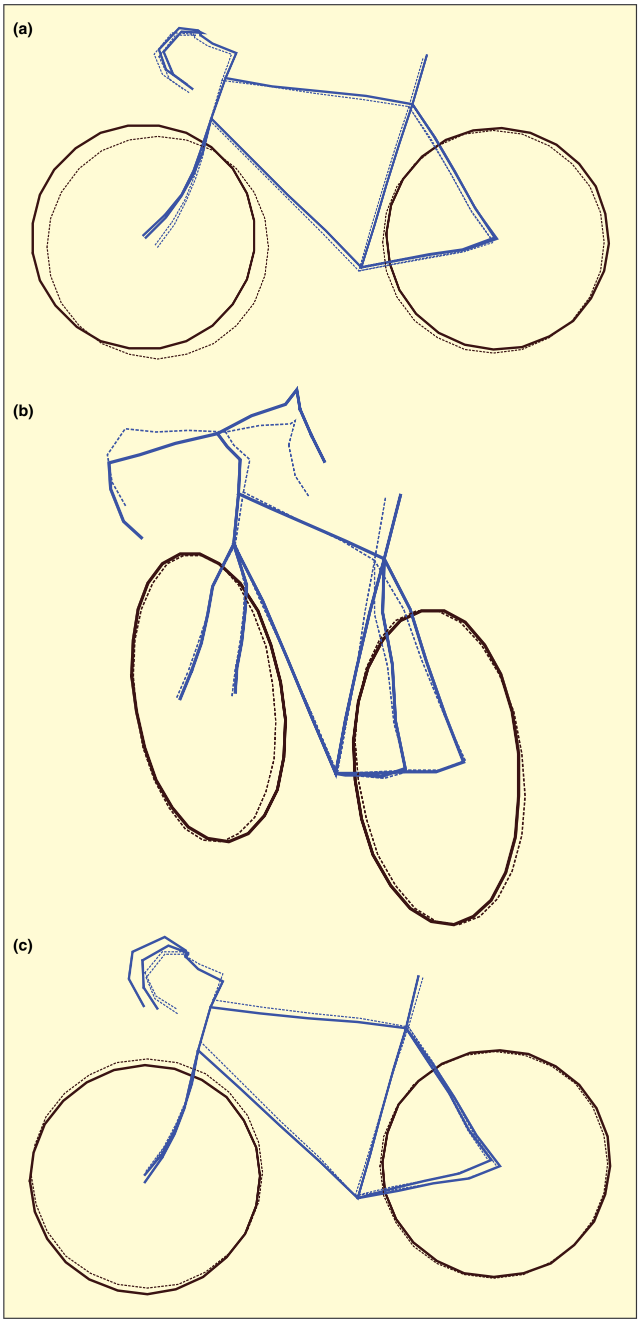

Figure 5. (a) Front-to-back mode of fork – 33.5 Hz; (b) Stem-torsion mode – 44.0 Hz; (c) Stem-bending mode – 54.3 Hz.

modes that can be extracted within the 10-100 Hz band. Most of the modes on the handlebars are not detectable. Only the first cantilever beam-like mode of the front fork and wheel is similar between the two configurations. The natural frequency of that mode is shifted from 33.5 Hz to 27.8 Hz with the presence of the cyclist.

Operational Modal Analysis. One might ask how close are the lab results when compared to real-life road conditions. Operational modal analysis (OMA) can help to answer this important question. Because a bike is a light structure, one could suspect that its modal parameters would be affected by its boundary conditions. The main difference between the lab (with a cyclist) and the real-life outdoor conditions is that in the lab, no parts are moving including the wheel.

First developed for civil engineering, OMA is continually being applied to mechanical structures such as aircraft, trains, vehicles and operating machinery for determining modal parameters. When compared to classical modal analysis, OMA presents important advantages:[2]

- Structures impossible or difficult to excite by externally applied forces can be tested.

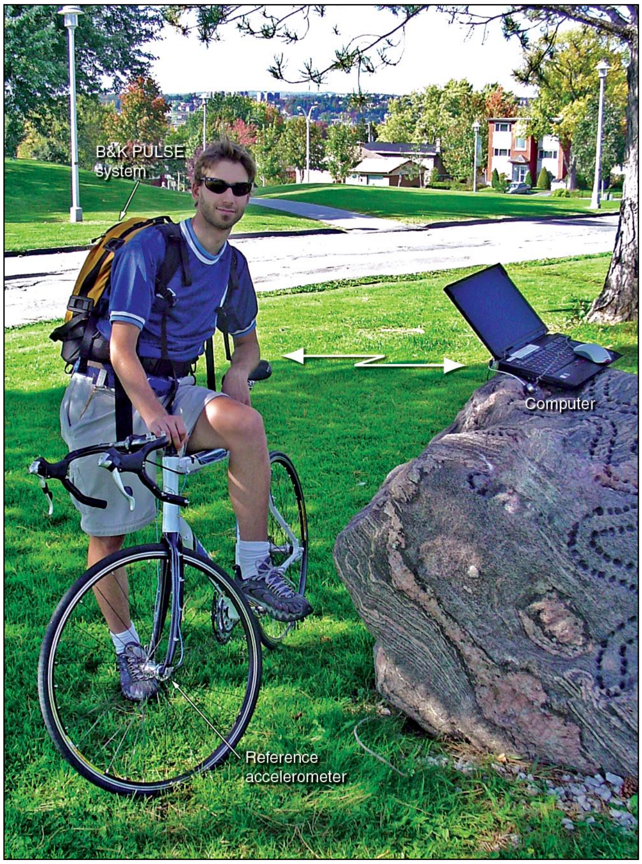

Figure 6. Setup for the OMA.

- Modal model represents real operating conditions.
- Testing can be performed *in situ* without interruption and in parallel with other applications.
- Simple and rapid setup.
- Simple test procedure similar to operating deflection shapes (ODS).
- OMA of a road bike is used here to validate that the data obtained in lab conditions can yield accurate modal parameters.

Experimental Setup. The instrumentation used for testing a road bike is limited to three triaxial accelerometers, a portable data acquisition system, a rough road surface and a sunny summer day! Figure 6 shows the setup. One reference triaxial accelerometer, PCB Model 356B11, is installed on the left side of the front axle. Two roving triaxial accelerometers of the same model are used to measure 20 points located on the frame and components. The cyclist is asked to ride normally (sometimes pedaling and sometimes not) on a selected road with cracked asphalt surface. The Brüel and Kjær Pulse™ portable system is placed in a backpack carried by the cyclist. During the acquisition, all the measured signals are transferred in real time to a laptop computer on the side of the road with a long-range, high-speed wireless connection. The signal is recorded for 100 sec for each set of measurement locations.

OMA Results. The frequency-domain decomposition (FDD) and the enhanced FDD (EFDD) technique are both used to analyze the data. The FDD technique estimates the modes using a singular value decomposition (SVD) of the spectral density matrices. This decomposition corresponds to a single degree of freedom (SDOF) identification of the system for each singular value. This technique allows identification of natural frequency and unscaled mode shape. Damping characteristics, more accurate estimation of resonance frequencies and improved estimation of the mode shapes can be obtained using EFDD.[3]

The main results from FDD and EFDD are shown in Table 3. The FDD and EFDD techniques give approximately the same results for the modal parameters. Table 4 shows the modal parameters comparison for MIMO (with a cyclist) and OMA. Mode 1 (21.9 Hz) is associated with a vertical bouncing motion of the entire bike. There is no deformation of the structure at this frequency, and all measured DOFs are moving vertically. In a previous experiment,[1] the same mode was found at 22.5 Hz, which is consistent with the present analysis.

An examination of Table 4 shows that classical and operational modal analyses extract the same modes at around 50 Hz, 245 Hz and 290 Hz. The important front-to-back mode of the fork at around 30 Hz is also extracted in both classical and operational modal analyses with a slight increase in frequency for the OMA. This shift in frequency is probably due to a change of position of the rider between the static and road tests.

Compared to OMA, the MIMO test shows additional modes at 87.5, 148.0 and 174.0 Hz. It is believed that there is not enough energy in the road excitation in the OMA test to adequately excite these modes. The damping ratios are generally of the same order of magnitude between the two techniques but systematically lower for the MIMO test.

The generally good correlation between MIMO and OMA testing allows one to conclude that lab testing, which is much more repetitive and easier to conduct, can provide adequate modal parameter estimation. Lab testing also allows measuring the wheel vibration to extract their modal contribution.

Operating Deflection Shapes. Operating deflection shapes (ODS) is a simple technique to implement and provides very useful information for understanding and evaluating the "real-life" dynamic behavior of a machine, component or an entire structure.[4,5] For bike dynamic analysis, it is quite useful to find how much a bike dynamically distorts and what part shows the maximum displacement and it what direction.

The setup for this experiment consists of a custom-made treadmill (Figure 7) driven by a 10-HP electric motor. The rolling surface provides enough space for the cyclist to move freely while pedaling. The speed can be constant (manual mode) or controlled by the real-time position of the rider. The inclination of the platform can be set between –3° and +17° to simulate descent and climb.

An ODS can be defined from any forced motion either at a moment in time or at a specific frequency.[5] For this experiment and to study the dynamics of a bike rolling on a rough road, excitation is provided by a 0.5 in. wood stud glued to the treadmill belt. At 18 km/hr, the rider impacts the stud once every second. Response data are measured at 39 locations along the fork, on the handlebars and on the bike frame. A reference accelerometer is located on the front axle. The auto-spectrum and cross-spectrum are averaged for each DOF and then processed in ME'scopeVES software to get the ODS FRFs, which are used to animate the structure at a particular frequency.

Figure 8 shows a typical auto-spectrum acquired during the test. The spectrum power is maximum around 30 Hz. Figure 9 shows the operating deflection shape at 34 Hz, which corresponds to the front-to-back mode of the fork and front wheel. A large amplitude is also noticeable at the handlebar. This is an important element, because it is directly linked to the hand comfort of the cyclist.

In lab conditions on a treadmill, the excitation and cyclist attitude are well controlled, so repetitive results are obtained. The ODS technique is then a useful technique to compare the vibration dynamics of bikes to compare, the influence of material, geometry or components.

Road Input Force Characterization

Road irregularities like cracks or potholes can be considered as excitation sources that can generate important force loadings. In the study of the dynamics of a bike, for modal analysis and for the measurement of frequency response functions, it is very good practice to have an appreciation of the excitation forces. An instrumented bump was designed to acquire *in-situ* wheel force loadings; it uses the principle of action-reaction of Newton's first law. Also, an instrumented hub was developed to measure forces at the fork and the frame wheel dropout.

Instrumented Bump. The instrumented bump is schematically described in Figure 10. An aluminum top plate is connected to a steel base using a three-point connection configuration. The impact object is a round stud rigidly attached to the top plate with a rigid support. Two PCB triaxial force sensors (Model 260A01) are used for the two connecting points right under the impact zone. A single steel ball bearing is used to support the other end of the plate. The vertical force F_v and horizontal force F_h are located at the same vertical plane of the force transducer. The ball bearing is located far enough to counterbalance the bending moment produced by F_h. The sum of the two measured vertical and horizontal forces corresponds to the total vertical and horizontal forces applied by the wheel to the impact stud. With the action-reaction principle, the measured forces correspond to the force loading imposed to the wheel. Note that for simulating a crack, one could replace the impact stud and its support by a U-channel mounted flush to the floor. Figure 11 shows a picture of a front wheel about to impact the instrumented bump stud.

A typical measurement of the time variation of the vertical force F_v is shown in Figure 12. Two peaks that correspond respectively to the impacts of the front and rear wheels are shown. As expected, the rear wheel peak amplitude is slightly higher than the front wheel due to the mass distribution of the cyclist on the bike. It is interesting to note that the top part of the peaks is tapered. It is believed that this is due to the fact that, at the maximum force, tire air pressure is contributing to the reaction force. Because the tire flanks are progressively pinched, the rubber compression of the flank over the rim also contributes to the reaction force and produces a nonlinear reaction force. Figure 13 shows the energy spectral density of the reaction force for the front wheel. This shows that most of the impact energy is limited to the frequency band within 0-50 Hz.

Instrumented Hub. Bicycle manufacturers are particularly interested in fork and frame dropout forces, because this represents the input loading to the structure on which they can control the characteristics through an appropriate design. Finite-element studies are useful if the loads are known. To measure real-life loadings at fork and frame dropouts, dedicated instrumented hubs were developed using strain gauge technology. To adequately measure these forces, one must adequately take into account end support conditions of the axles. The flexural dropout stiffness influences

Table 3. Modal parameters from FDD and EFDD techniques.

Mode	Frequency, Hz and Damping Ratio for EFDD (%) FDD	EFDD	Description
1	21.0	21.9 (15.3)	Vertical motion of bike
2	33.0	34.1 (13.3)	Front-to-back motion of fork
3	51.5	51.4 (6.1)	Frame torsion and lateral motion of fork
4	247.0	247.3 (1.4)	Lateral motion of fork and 3D motion of handlebar tips
5	290.0	289.7 (1.7)	Lateral motion of fork, 3D motion of handlebar tips and first bending mode of down tube

Table 4. Modal parameter comparison between MIMO and OMA.

Frequency, Hz(Damping Ratio) OMA (EFDD)	MIMO	Description
21.9 (15.3)	–	Vertical motion of bike
34.1 (13.3)	27.8 (7.1)	Front-to-back motion of fork
51.4 (6.1)	48.9 (5.8)	Frame torsion and lateral motion of fork; *MIMO only*: Front wheel first bending mode
–	87.5 (1.6)	Front wheel second bending mode; stem torsion
–	148.0 (0.9)	Lateral motion of fork and front wheel 3rd bending mode
–	174.0 (2.6)	Lateral motion of handlebar tips and 3D motion of fork
247.3 (1.4)	243.0 (0.7)	Fork and handlebar tips lateral motion; *MIMO only*: front wheel fourth bending mode
289.7 (1.7)	290.0 (0.7)	Lateral motion of fork; *MIMO only*: first bending mode of top tube and seat stay; *OMA only:* 3D motion of handlebar tips and first bending mode of down tube

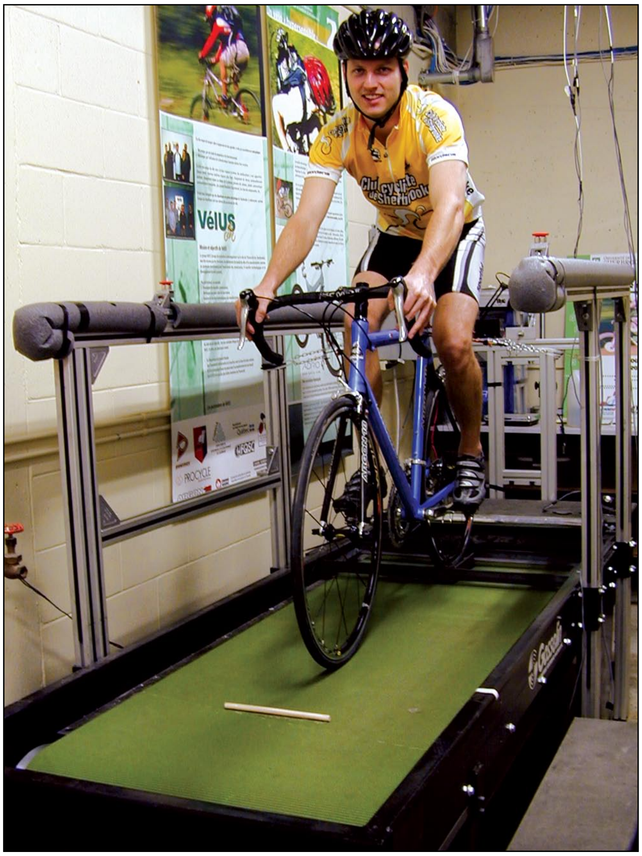

Figure 7. Custom-made treadmill.

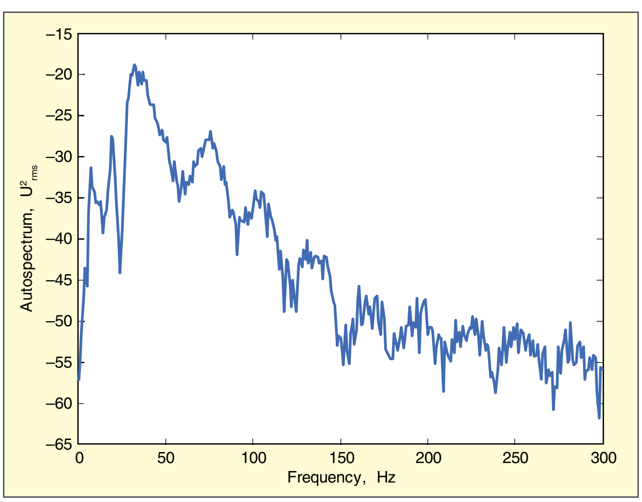

Figure 8. Typical autospectrum from ODS measurements.

the global hub stiffness, which in turn influences the sensitivity of the instrumented hub. To overcome this coupling effect, a new hubset design was proposed and tested to measure vertical and horizontal forces on each end of the axles. This design allows one to obtain pin-pin boundary conditions for each axle. Mechanical decoupling between the force components is guaranteed by an adequate positioning of the strain gauges. Calibration and *in-situ* measurements demonstrated that this new hubset design allows accurate measurements to be obtained for both small and large loads. Figure 14 shows the rear wheel instrumented hub. The dropouts have been modified to allow for the special instrumented axle and wiring. The instrumented hubs are not built from commercial hub parts but with specifically designed components for force measurement purposes. Figure 15 shows the time variation of the vertical forces at the two fork dropouts measured at the front hub while standing and climbing a hill. The left-right oscillating movement of the bike generates a typical alternating force pattern.

The instrumented bump and the instrumented hub can provide

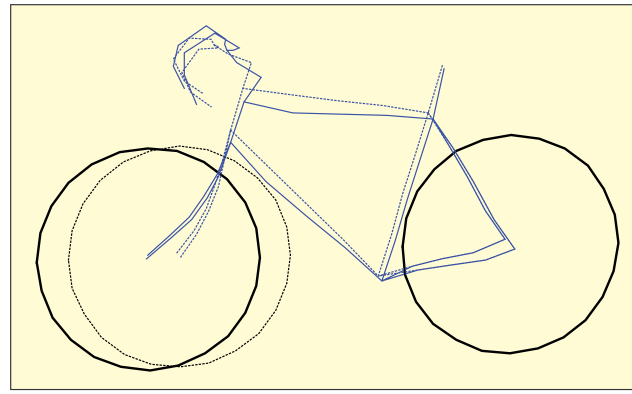

Figure 9. ODS at 34 Hz (broken line – undeformed).

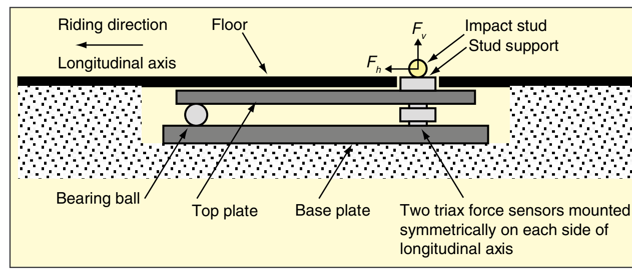

Figure 10. Schematic of instrumented bump.

Figure 11. Front wheel about to impact wooden stud mounted on instrumented bump.

valuable data for developing several bike designs. For example, they can provide frequency response functions or force transmissibilities between the road and axle to study the dynamic behavior of the wheel or the tires. They can also provide accurate *in-situ* force loadings for finite-element analysis of the frames or fatigue life calculations.

Road Bike Comfort

Comfort is one of the major concerns of road cyclists and makers of road bikes. Long-distance cyclists can spend several hours on their bike during a single ride. In the absence of well-established definitions, we propose the use of the terms "static comfort" and "dynamic comfort" to discriminate between two types of comfort. Static comfort is related to the proper positioning of the cyclist on the bike, which is in turn related to bike size, selection of proper component size, the morphology and flexibility of the cyclist and his or her ability to adapt.

Dynamic comfort is related to the perceived vibration transmitted at five contact points on the cyclist: the hands, the feet and the buttocks. On a rough road, compression of soft human tissues, energy transfer and repetitive motion at the handlebars produce symptomatic conditions[6] creating a level of fatigue that is eventually perceived by the cyclist as uncomfortable. In specialized road

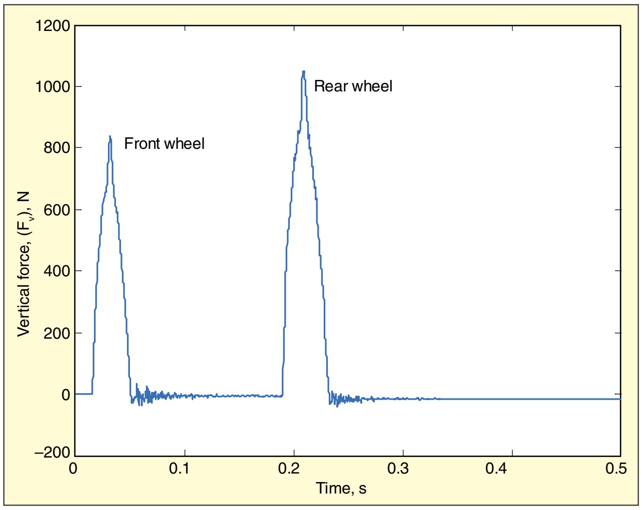

Figure 12. Typical vertical force measurement loadings at front and rear wheels.

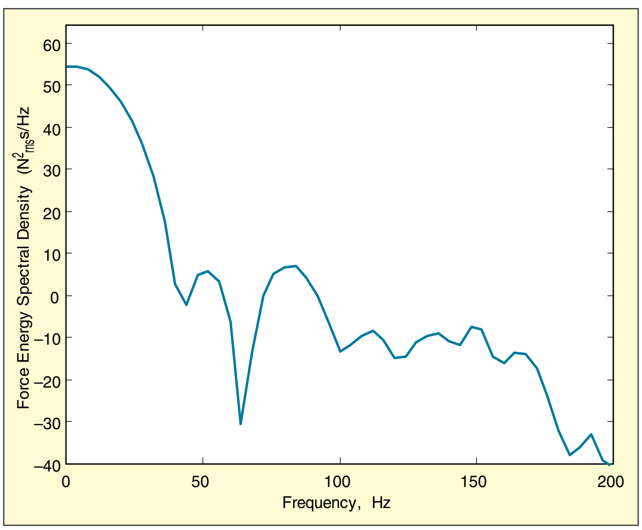

Figure 13. Energy spectral density of reaction force of front wheel.

bike magazines, the omnipresence of the word ‘comfort’ illustrates the fact that dynamic comfort is a primary concern. Surprisingly, scientific literature on bike comfort is almost nonexistent, and research work must be done to improve our understanding of this bike characteristic.

Dynamic comfort is also directly related to the quality of the road surface. On a newly paved and ultrasmooth road, the dynamic comfort is not an issue, because there is virtually no vibration energy transferred to the rider. Two “typical road pavement conditions” that cause two different types of excitation can be defined – cracked roads and coarse roads.

A cracked road contains cracks and potholes sufficiently spaced to allow vibration of the bike to vanish between events. The excitation can be considered as a series of successive impacts. A coarse road transmits continuous random excitation to the wheels. Asphalt or concrete roads with a rough but uniform surface structure are included in this definition. The excitation can be characterized as random and continuous.

To study the dynamic comfort of a road bike, acceleration measured near the hands can be considered. However, when a cyclist applies an increasing force on the handlebars, more vibration energy is transferred to the hands and the perception of discomfort increases. However, the acceleration level decreases drastically. Because of this inversely proportional behavior of acceleration versus perception of discomfort, the acceleration is not the best physical quantity to use for developing a metric. The force level transmitted to the hands seems to be a better choice, because the magnitude of the force is somehow linked to the perception. Based on previous work,[7] a commercial bicycle stem instrumented with

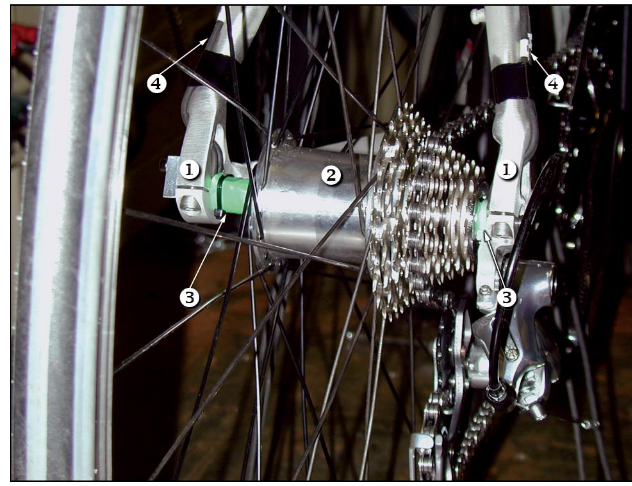

Figure 14. Rear wheel instrumented hub : ① – Frame dropout; ② – Dedicated hub body; ③ – Instrumented section of the axle; ④ – Signal wire connectors.

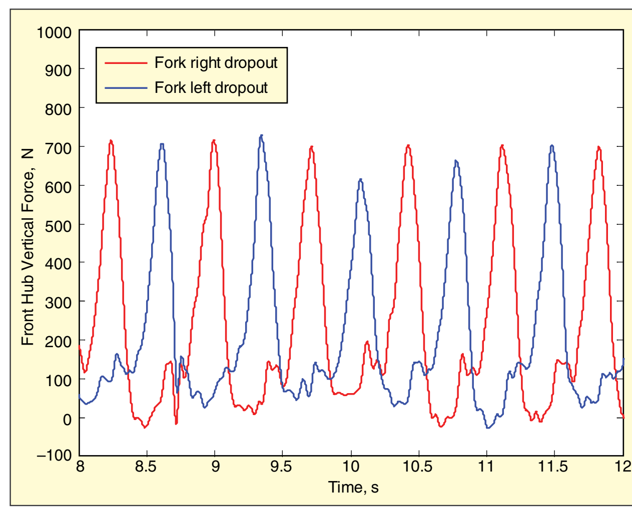

Figure 15. Typical vertical force measurement at front wheel hub.

strain gauges (Figure 16) is used to measure the total force imposed to the hands of the cyclist. Four strain gauges in a full-bridge configuration allow measurement of the vertical force.

To study the cracked road, a lab procedure involving the treadmill is used. A wooden stud is glued to the surface to provide the excitation. One of the key elements is to obtain a good repeatability of the testing protocol. Using the DC force level on the handlebars as a parameter controlled by the cyclist allows drastic improvement in repeatability of the test. Figure 17 presents 20 successive impacts during the same test run. The measurement variability is relatively small for such an excitation. Averaging 20 impacts allows calculation of a force energy level associated with the dynamic behavior of the front part of a bike. This value can then be used to perform a comparative comfort study between different component selections for the entire bike. This topic is the object of an ongoing project.

Fatigue life prediction

The fatigue life prediction of bike frames and components is an important issue, because it relates to the durability and safety of a bike. European standards EN 14781 and EN 14766 aim to ensure that bicycles will be as safe as practically possible This will certainly have an important influence on developing techniques and tools to predict fatigue life for bikes. Most of the cracks and failures appear near the root of weld joints because of stress concentrations. Different techniques are available to predict the fatigue life of metallic materials. Most of them however are not suited for structures like a bicycle, which uses thin-walled tubes. The techniques are also quite complex, because they require an accurate description of the weld joint.

Figure 16. Instrumented stem to measure vertical force on handlebar.

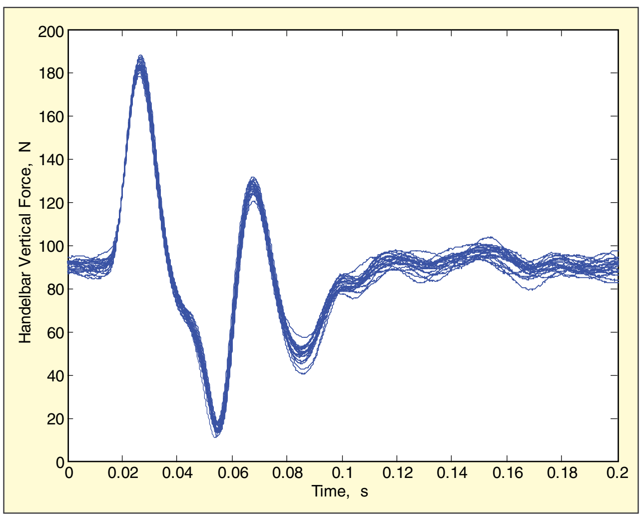

Figure 17. Force time variations at handlebars for repetitive impact excitation on treadmill; small dispersion demonstrates that the protocol used yield to an acceptable repeatability.

The hot-spot technique avoids these limitations and is relatively simple to use. It requires measuring or estimating, with the finite-element method, the stress level at two specific locations near the weld (Figure 18). These stress levels are then used to extrapolate a stress level, or hot spot, at the root of the weld joint. Using the appropriate S-N curve, fatigue life can be estimated.

The hot-spot technique is used for large structures made of thick plates like those used to build ships or offshore platforms. Engineers in the VélUS group were interested in exploring the use this technique for thin, circular, aluminum tubes. In one study,[8] a large number of aluminum bike tubes welded in different configurations were instrumented (Figure 19) with miniature strain gauges to measure the hot-spot stress level and were tested on a fatigue machine. The S-N hot-spot curve shown in Figure 20 for aluminum 6061-T6 was then obtained. This study shows that, with the appropriate curve, the hot-spot technique can be used to predict the fatigue life of bike frames and components fabricated with thin, circular, aluminum tubes.

Conclusions

Bicycle technology is in constant evolution, and the industry is always looking for new designs and new technology. Understanding and mastering the dynamic behavior of a bike is not an easy task and requires more fundamental and applied research. Establishing collaboration with specialized university research groups is an efficient way for manufacturers to face these technical and scientific challenges. The more manufacturers can learn and understand about the dynamic response of their products, the more they will be able to benefit both current and potential riders.

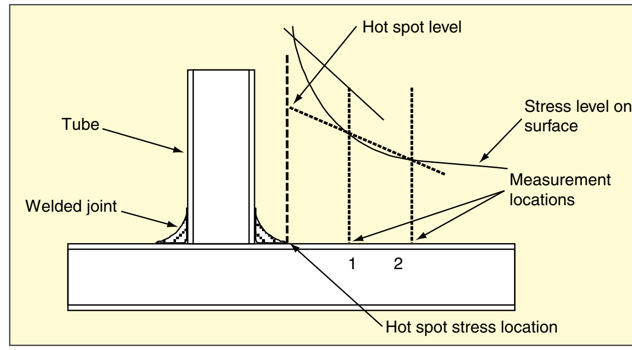

Figure 18. Hot-spot stress level estimation.

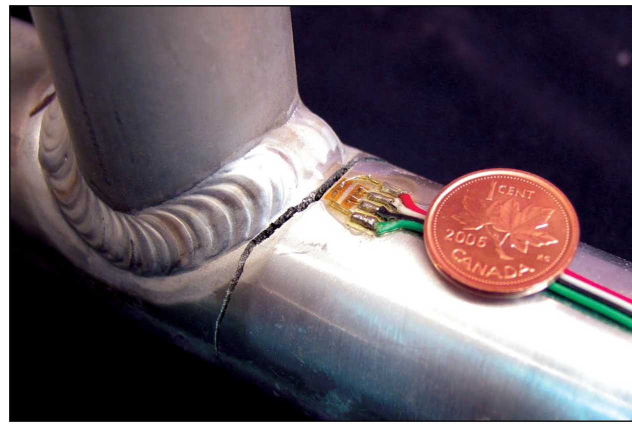

Figure 19. Bicycle tube equipped with two miniature strain gauges to measure the hot-spot stress level; crack shows that tube has been tested to measure fatigue life.

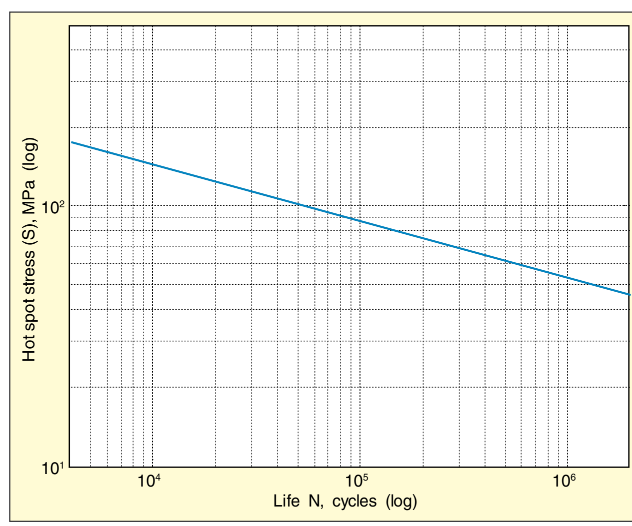

Figure 20. S-N hot-spot curve for 6061-T6 welded aluminum thin-wall tube.

References

1. Richard, S., and Champoux, Y., "Modal Analysis of a Road Bike's Front Components," Proceedings of IMAC XXII, Dearborn, MI, 2004.
2. *Brüel & Kjær Magazine*, No.1, pp. 18-21, 2003.
3. Batel, M., Svend, G., Møller, N., and Herlufsen, H., "Ambient Response Modal Analysis on a Plate Structure," Proceedings of IMAC XXI, Kissimmee, FL, 2003.
4. Døssing, O., "Structural Stroboscopy – Measurement of Operational Deflection Shapes," *Sound and Vibration*, August 1988.
5. Schwarz, B. J., and Richardson, M. H., "Introduction to Operating Deflection Shapes," CSI Reliability Week, Orlando, FL, October 1999.
6. Richmond, D. R., "Handlebar Problems in Bicycling," *Clinics in Sports Medicine*, 13, 165-173, 1994.
7. Champoux, Y., *et al.*,"Measuring the Dynamic Structure Load of an Off-Road Bicycle," *Experimental Techniques*, 28, 33-36, 2004.
8. Pelletier, M., "Utilisationde la Méthode Hot-Spot pour des Composantes Tubulaires Soudées à Parois Minces en Aluminium," Master Degree thesis, Mechanical Engineering Dept., Université de Sherbrooke, 2005.

The author can be reached at: yvan.champoux@usherbrooke.ca.