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Analysis of Bicycle Shimmy and Relevant Bicycle Compliances

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ABSTRACT

The paper deals with bicycle shimmy, a vibration of the steering assembly which may unexpectedly occur at high speed, putting the rider's safety at high risk, and aims to contribute to the understanding of the phenomenon by bringing analytical results related to experiments on the road and indoor. The analysis of both shimmy data recordings and indoor measurements highlights the existence of a deformation mode of the bicycle which acts mostly along a longitudinal axis. When the bicycle is resting with both wheels on the ground and the rider's hands on the handlebar, the vibration mode has an eigenfrequency very close to the shimmy frequency, a result that is consistent with and supports the conjecture proposed in [8]. The bicycle compliance related to this deformation mode seems well described by a torsional spring about the *β-axis* [4], which is an essential term of bicycle models able to predict the shimmy onset. Finding where this compliance originates from, distinguishing the contributions of the fork, frame, wheels and tires is the goal of indoor tests. The contributions of wheels and tires appear to be relevant at a first assessment.

Keywords: bicycle shimmy, bicycle compliances, structural resonance

1 INTRODUCTION

Bicycle shimmy manifests to the rider as a nasty oscillation of the steering assembly. Focusing on road-racing bicycles, shimmy may onset while riding downhill at speed higher than about 14 m/s without any apparent reason, and will disappear only once the speed is decreased down to 10-11 m/s. Shimmy makes it difficult to ride the bicycle and even brake, and gives ugly physical sensations and fear of falling or totally losing control of the direction of the bicycle. As such it is extremely scary and dangerous for the safety of the rider.

Bicycle shimmy is known to manufacturers and, despite occasionally it is talked about in popular journal and cycling web sites [1-2], it is largely unknown to riders. From a scientific point of view (see. E.g., [3-7]), the shimmy mechanism is relatively understood, but the conditions causing the shimmy onset, apart from the high speed, are not at all known. The randomness of shimmy onset makes very difficult to find conclusive confirmation in on-road experiments to working assumptions and analytical results. A large number of parameters are involved, including structural properties of the bicycle, tyre characteristics, rider mass, geometry and riding style, and quality of asphalt.

The contribution of the present paper is twofold. In the first part, on-road shimmy tests are analyzed to understand the vibration modes of the bicycle during the shimmy phenomenon. The on-road tests consist in riding the bike downhill up to about 16 m/s, which is the speed that triggers the shimmy for this particular bicycle and rider. The shimmy condition persists until the speed decreases down to about 11 m/s at the end of the downhill. The motion of the bicycle is recorded by means of 6 IMUs (Inertia Measurement Units), four located on the frame and two on the front fork, according to Figure 1.

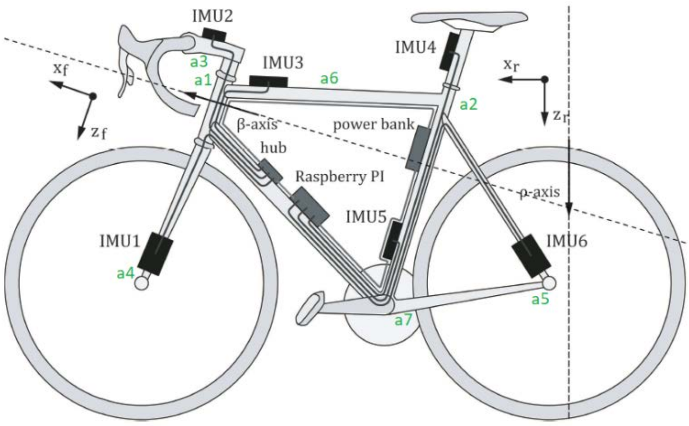

Figure 1. Locations of Inertial Measurement Units of on-road tests (IMUi, i=1:6) and of accelerometers of indoor tests (ai, i=1:7)

The second part of the paper reports on indoor tests performed on the full bicycle, with the rider on it. The purpose of the tests is to compare the behavior (frequency response) of the stationary bicycle resting on the ground as in normal road ride and that of the bicycle with both hubs locked, in one case, and with the rear hub locked and the front one free in the other case. The tests are performed by hitting the bicycle frame by an instrumented hammer at the head tube, and recording the consequent lateral accelerations of seven points of the frame and front fork, located as it is shown in Figure 1 (ai, i:1,7 show the accelerometer positions). It is assumed that this perturbation can excite the vibration modes involved in shimmy, and that constraining the hubs allows to distinguish the contribution of the wheels and tires compliances to the shimmy vibration mode.

The paper is organized as follows. Section 2 illustrates some fundamental findings about the behavior of the rear and front frames of the bicycle under normal running conditions and during a medium intensity shimmy. Section 3 illustrates the indoor experiments and the relevant frequency responses of the rear frame and fork. Section Conclusion discusses the correspondences and differences between the bicycle behavior on-road and indoor.

2 ON-ROAD EXPERIMENTS

In November 2017, a professional road racing bicycle equipped with 6 IMU, each able to measure the three orthogonal components of the linear acceleration and of the angular velocity, was used to repeatedly ride along a downhill road where maximum speeds of about 17-18 m/s could easily be reached. In one of these descents, a medium intensity (compared, for example, with the ones described in [6, 8]) shimmy onset spontaneously. The bike instrumentation also included GPS and forward speed sensor, and a central single board computer (Raspberry Pi) driving the six microcontrollers (Arduino boards) hosting the IMUs. Signals were sampled every 0.005 s (200 Hz), and the sampling was triggered by the central unit with a single digital output (DO) signal to the 6 Arduino boards to ensure the synchronous sample of all IMU outputs. This is an essential measure for correctly detecting the relative phase shifts of the signals, which in turn are essential for detecting any flexibility of the parts of the bicycle, as a single sample delay gives a phase shift of 13.5° for 200 Hz sampling of a 7.5 Hz sinusoidal signal. More details on the instrumentation setup can be found in [9].

2.1 On-road tests frequency domain analysis

In this section, the acquired data are analysed in the frequency domain in order to highlight the different behaviour of the bicycle in normal riding or during the shimmy phenomenon. Since shimmy interests mostly roll and yaw motions, only roll and yaw will be considered in this analysis.

To perform a direct comparison, IMU data have been processed in the same reference frame. In Figure 1, the reference frame of the front frame IMUs $x_f y_f z_f$ and that of the rear frame IMUs $x_r y_r z_r$ are shown (pitch y axis completes a left-handed frame). All signals were filtered with a an 8-pole low-pass Butterworth filter with 20 Hz bandwidth. Angular accelerations were derived from the angular velocities by the central-difference formula.

In Figure 2, the spectra of the angular acceleration measured by the four IMUs on the rear frame is depicted in shimmy and no shimmy conditions. For both roll and yaw accelerations (referred to reference $x_r y_r z_r$), when the shimmy occurs the acceleration levels grow at any frequency, with a peak around 7 Hz. Interestingly, while for the yaw acceleration the signals of the four IMUs are very similar in the considered interval, the signals referring to the roll accelerations are very similar only up to 4 Hz.

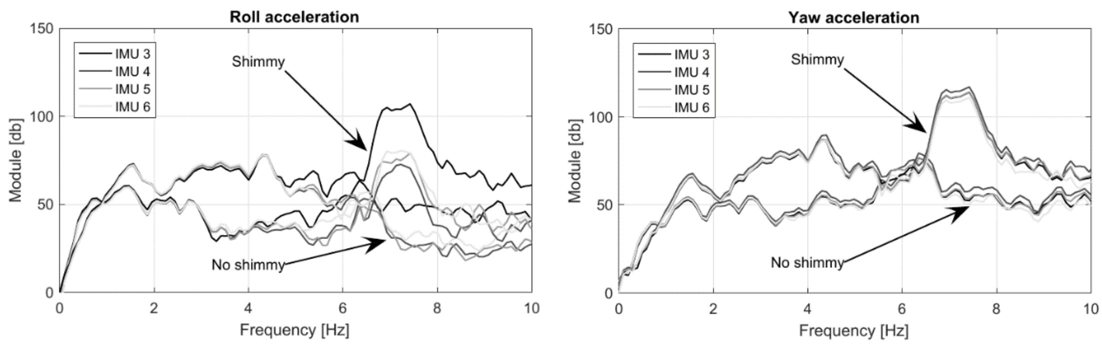

Figure 2. Spectra of the angular accelerations during shimmy and no-shimmy riding. Left: roll acceleration. Right: yaw acceleration.

Figure 3 right shows the relative phases of the roll and yaw accelerations during the shimmy phenomenon. The IMU 3 signal was taken as a reference (zero phase at any frequency). IMU 3 is located on the horizontal tube near the steering hub (see Figure 1). From the figure, it can be observed that all the yaw acceleration signals have the same phase. This can be interpreted as a

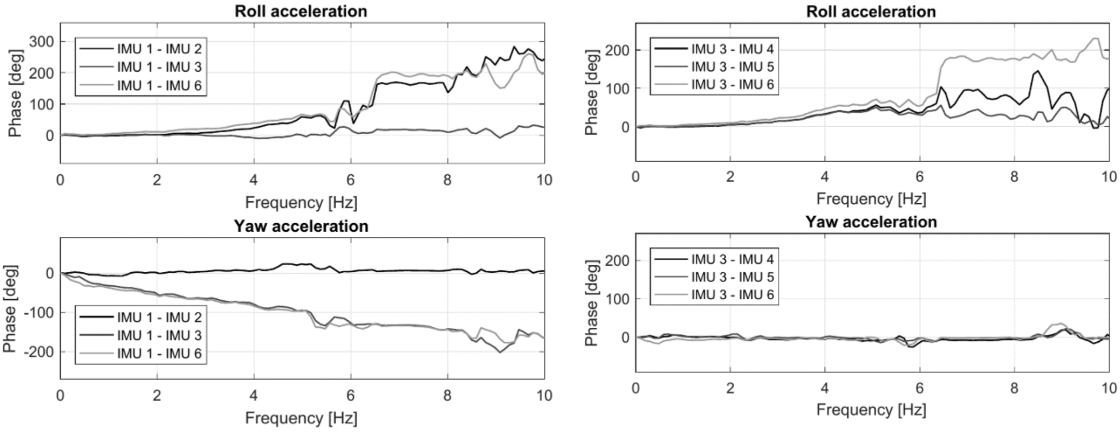

Figure 3. Relative phases of the angular acceleration measured at IMUs for roll (top) and yaw (bottom) motions. Left: fork. Right: frame.

rigid type motion of the frame with respect to the yaw degree of freedom. When the roll acceleration is considered, IMU 6 (located at the rear wheel hub, Figure 1) shows a clear phase change of 180° at approximately 6.5 Hz. At the same frequency, also the signal of IMUs 4 and 5 show a phase change, although smaller. This can be interpreted as a deformation of the frame during the shimmy motion along the longitudinal axis, with an eigenfrequency of about 6.5 Hz. Also, given the very quick change in the phase of IMU 6, the damping related to this motion is quite small. Given the much smaller change in the phase of the signals of the other two IMUs, the deformation of the frame along the longitudinal axis is mostly due to a deformation of the rear part of the frame.

In Figure 3 left, also the fork is considered. In particular the relative phase shifts of roll and yaw accelerations of the IMUs 2, 3 and 6 with respect to IMU 1 are shown. Roll and yaw refer to the respective local reference systems of the two bodies, i.e. $x_f y_f z_f$ for the front frame and $x_r y_r z_r$ for the rear frame. If the roll acceleration is considered, the fork shows a deformable mode with eigenfrequency around 6.5 Hz. This eigenfrequency is basically the same frequency found for the deformable motion of the rear frame with respect to the roll acceleration. Moreover, the handlebar is in phase with the horizontal tube of the rear frame and the two hubs have the same reciprocal phase. Referring to the yaw motion, the fork acts like a rigid body. The relative phase of the fork and the rear frame during the motion varies with frequency and they appear to be almost in opposite phases for frequencies near the shimmy frequency.

The plots of the lateral linear accelerations measured by the rear frame IMUs during shimmy are shown in Figure 4, together with their phasor representation. The oscillation frequency is about 7 Hz, and the phase shifts of 90° from IMU 3 to IMU 6.

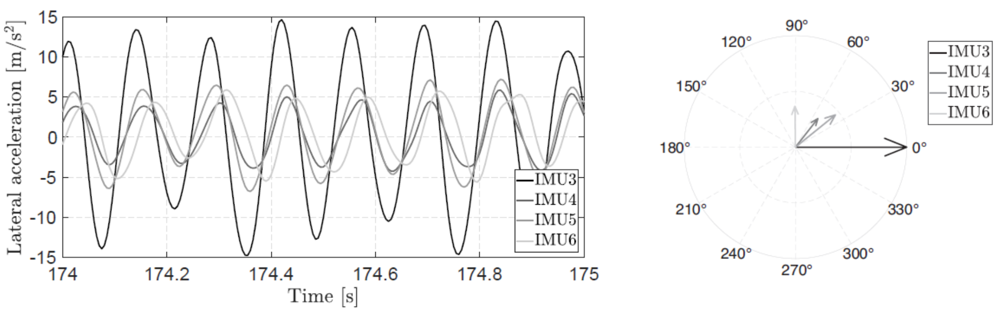

Figure 4 Lateral linear accelerations $\boldsymbol{a}_{y_r}$ measured at rear frame IMUs

3 INDOOR EXPERIMENTS

The frequency analysis performed on the data collected during the road tests has shown deformation modes of both the rear and the front frames of the bike at frequencies close to the shimmy frequency. Moreover, these deformation modes are not present during the normal riding of the bike, i.e. when no shimmy is present.

Indoor tests are performed on the full bicycle, with the rider on it, to understand and characterize the different modes. The aim of the tests is to identify the deformation modes of the bike that are most likely involved in the shimmy phenomenon, and to distinguish the contribution of the frame, fork and wheels compliances to them. Being the deformation of the frame during shimmy mostly around a longitudinal axis, only lateral accelerations are considered.

The tests are performed by hitting the bicycle in a fixed point on the head tube by an instrumented hammer and recording the consequent vibrations by accelerometers located in different positions of the frame and of the front fork.

In Figure 1, the locations of the seven accelerometers used for recording the lateral accelerations of the frame are shown. The excitation point is on the opposite side of the head tube with respect to the accelerometer a1.

The tests have been carried out in four different configurations of the bicycle in order to assess the specific contribution of frame, fork and wheels (including tires) to its overall lateral compliance. The configurations differ in the way in which the bicycle is fixed to the ground:

- Configuration 1: bike with both wheel hubs fixed. The rear wheel hub is fully constrained, while the fixturing of the front wheel hub has a very low longitudinal stiffness in order to avoid the over-stiffening of the bike frame (Figure 5a).
- Configuration 2: rear wheel hub fixed. Front wheel positioned on a plate allowing a free lateral motion (Figure 5b). The lateral motion is allowed by means of cylindrical bearings below the plate.
- Configuration 3: rear wheel hub fixed. Front wheel resting on the ground (Figure 5c).
- Configuration 4: bike with both wheels resting on the ground. The equilibrium of the bike is obtained by the rider lining with a shoulder on a wall.

Figure 5 Constrained characterization tests on the bicycle. The rear wheel hub is rigidly fixed to the ground in all of the three configurations. Front wheel constraint: a) wheel hub rigidly connected to the ground, b) wheel connected by a low friction sliding joint, c) wheel resting on the ground.

During the tests, the rider's hands were gripping the bend of the handlebar. Configuration 4 has been repeated also with the rider's hands off the handlebar.

Figures 6 to 9 show the transfer functions for the fork and the frame obtained for the four considered configurations with the rider's hands gripping the bend of the handlebar. By inspecting the figures, the following information can be obtained.

If the bike frame is considered (Figure 7 and Figure 9), in all cases, at low frequencies the frame shows a deformation around a mostly vertical axis with the front part of the frame (head tube and top tube) with opposite phase with respect to the other three points. As the frequency grows, the rotation axis seems to tilt backward as the phase of the central movement goes toward the phase of head and top tubes. Only in configuration 1, also the seat changes its relative phase with respect to the rear hub. The frame also shows an eigenfrequency in the range from 7.5 to 27 Hz depending on the fixturing configuration. The lowest frequency, 7.5 Hz, is obtained when the bicycle has both tires resting on the ground, and it is very close to the shimmy frequency identified in the road tests. Table 1 shows the lowest eigenfrequency values of each configuration.

	First eigenfrequency [Hz]
C1 – RH and FH locked	*27*
C2 – RH locked, FW roller	*10.7*
C3 – RH locked, FW on ground	*10*
C4 – RW and FW on ground	*7.5*
C4 hands-off	*10.3*

Table 1. First eigenfrequency (RH/FH rear/front hub, RW/FW rear/front wheel)

Referring to the fork, only in configuration 2 a deformation mode appears at 20 Hz. Below this range the forks behaves as a rigid body. In the deformation mode, the lower part of the fork moves with respect to head tube and handlebar. When a lateral constraint of the fork is considered (either a structure or the contact between tires and ground), this motion disappears. If the rider's hands are off the handlebar (Figure 10), at low frequencies, the handlebar has an opposite phase with respect to the fork and head tube. This motion is similar to the one seen on road tests.

In all of the considered configurations, due to the presence of the rider, the damping of the system is quite large and appears higher than the damping seen on the road tests. This may indicate that the rider during the shimmy phenomenon is interacting in a different way with the bike.

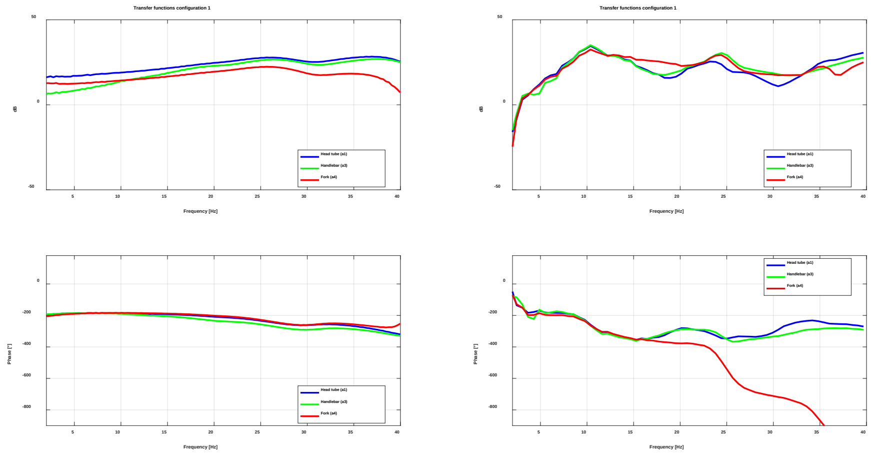

Figure 6. Transfer functions of the fork, configurations 1 and 2.

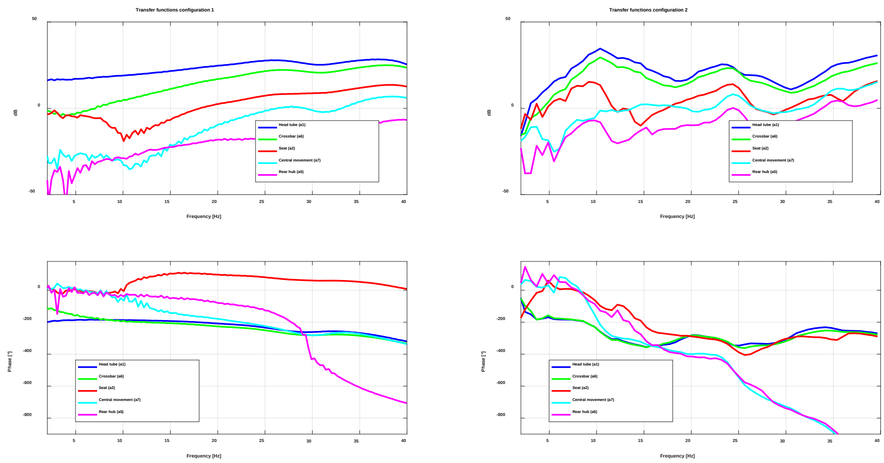

Figure 7 Transfer functions of the frame, configurations 1 and 2.

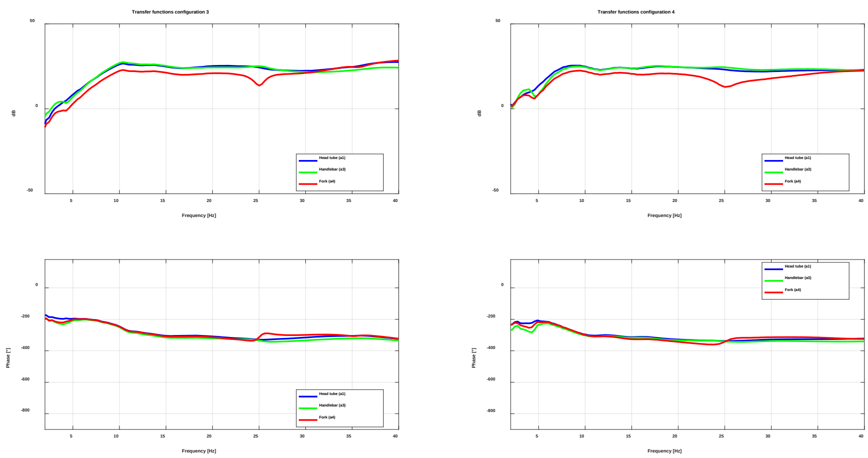

Figure 8 Transfer functions of the fork, configurations 3 and 4.

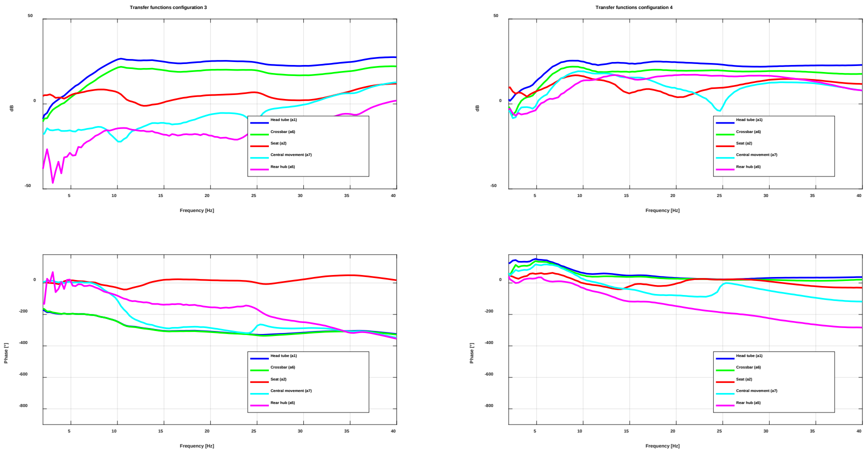

Figure 9 Transfer functions of the frame, configurations 3 and 4.

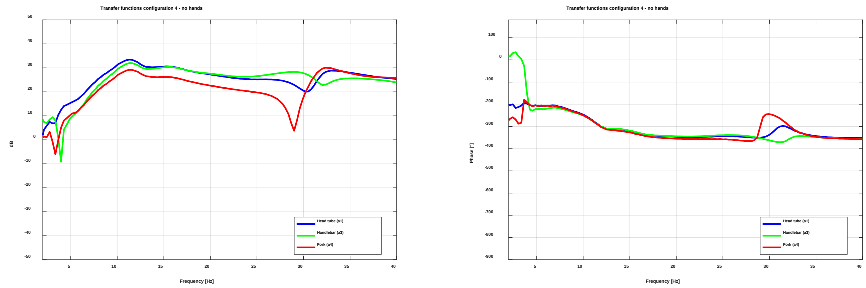

Figure 10 Transfer functions of the fork, configuration 4 with rider's hands off the handlebar.

4 CONCLUSIONS

The paper first presented the analysis of recordings of linear accelerations and angular velocities obtained during a medium-intensity genuine shimmy occurred along a steep descent with a road racing bicycle, and then of recordings of linear accelerations acquired indoor on the bicycle resting on the ground and / or constrained at the level of the hubs, aimed at highlighting the compliances of the frame, fork, wheels and tires that contribute to the shimmy onset.

The performed analysis shows that the bike cannot be considered as made of two rigid bodies at the shimmy frequency. In particular, the frame has a deformation mode which acts mostly along a longitudinal axis. This mode has an eigenfrequency very close to the frequency of the shimmy. Actually, when the bicycle is resting with both wheels on the ground and the rider's hands in the bend of the handlebar, the frequency of the shimmy and that measured indoor almost coincides, a result that is consistent and supports the conjecture proposed in [8].

The fork has a mode that deforms its lower part, but it is mostly restrained by the constraint put into action by the front tyre on the ground. A second mode gives a deformation of the handlebar with respect to the fork and can be seen from the on-road gathered shimmy data. Indoor experiments highlight this mode only in the hands-off case (bicycle resting on the ground, rider hands off the handlebar), probably due to the difficulty of exciting it when the rider's hands are gripping the handlebar.

The present work can give an understanding of the main deformation modes that can influence the shimmy phenomenon. Subsequent research should relate the vibration modes to multibody models (e.g., [10]) to identify precisely the compliance parameters of the bicycle components and of the rider. To correctly model the constraint between tyre and road, careful measures of the lateral and longitudinal forces and of overturning and self-aligning torques, as functions of side-slip and camber angles will be taken [11].

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