Fork bending self-oscillation on bicycles influencing braking performance

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1 INTRODUCTION

This work deals with a fork bending oscillation phenomenon observed during hard braking on bicycles. The observed oscillation is described with experimental data and an attempt is made to understand the underlying root cause. Therefore, a multibody model consisting of the front wheel and the fork is employed to simulate a braking maneuver. The self-oscillation is replicated in simulation and implications on the brake process are derived from it.

Fork and tire oscillations on bicycles are rarely described in scientific literature. An oscillation due to tire resonance on high-speed motorcycles was described by Cossalter [1]. However, the mentioned speed dependence is not found in the present case under investigation. Klug et al. [2] were the first to report an oscillation of the fork inclination angle during braking. They noticed oscillations in the front wheel speed signals measured with a speed encoder mounted on the fork. Measurements of accelerometers and gyroscopes placed on the fork near the hub showed these oscillations on the forks inclination angular rate and vertical acceleration as well. This makes the phenomenon relevant for suspension and braking control. They also described the distorting effect of fork bending on the wheel speed signal and the wheel slip calculation derived from it.

This work tries to identify a root cause of the fork bending oscillation and investigates its influence on the stopping performance.

2 PROBLEM DEFINITION

During the authors previous work, measurements with an instrumented bicycle were conducted. Knowing about the effect from [2] attention was drawn to the phenomenon. The bicycle was equipped with an inertial navigation system (INS), an inertial measurement unit (IMU) mounted on the fork near the hub and brake pressure sensors. The INS gives accurate information about the bicycles over ground velocity as well as its spatial orientation. The IMU gives high bandwidth signals of the angular velocity and acceleration of the fork. On the other hand, the pressure sensor gives information about the braking process.

In Fig. 1 measurement data from a hard braking maneuver is shown. The rider was instructed to brake as hard as possible and as consistent as possible whilst tolerating a small amount of rear wheel lift. The upper plot shows the front wheel speed v_{f} as well as the over ground velocity v_{ref} from the INS. A superimposed oscillatory noise on the front wheel speed signal can be seen. The brake pressure p_{B} is also shown, the oscillation persists even when the pressure is held constant. The middle plot shows the angular velocity $\dot{\varphi}$ of the fork bending. Finlly the lower plot shows the measured acceleration in riding direction as well as the acceleration perpendicular to the road surface. This means that the fork is bending back and forth in riding direction and the hub is moving up and down relative to the road surface.

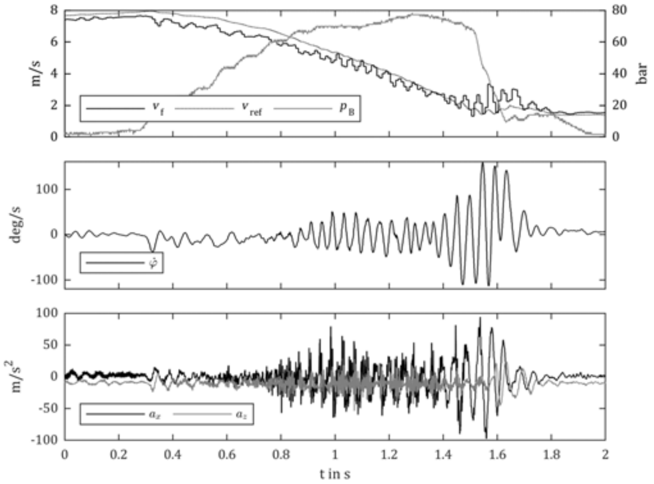

Figure 1: Measurement data showing strong additive oscillation noise. Taken from instrumented bicycle under hard threshold braking (rear wheel slowly lifting).

3 SIMULATION MODEL AND RESULTS

To understand the observed oscillatory motion a multibody simulation using a half bicycle model is set up. The topology is depicted in Fig. 2 and consists of the mass M suspended by the fork and the tire. The over ground velocity is assumed to be constant, thus the whole system is simulated in a moving coordinate frame. Consequently, only one-dimensional up and down movement of the mass is possible.

Using the results from [2] the bending of the fork is modelled as a rotary joint with the stiffness and damping coefficients c_{F} and d_{F}. The fork is tilted towards the ground with the caster angle φ_0. At the lower end of the fork the wheel is connected through a second rotary joint, representing the hub. The braking force is applied proportional to the brake pressure p_{B} by a friction brake as moment M_{B} between fork and wheel.

The wheel is modelled as a disk and has the parameters moment of inertia and mass as well as the undeflected radius r. There is a spatial contact force simulation between the wheel and the ground, allowing for separation. The contact force acts tangential and normal to the contact patch. The normal component F_{N} of the contact force is calculated from the deflection distance with the tire spring parameters c_{T} and d_{T} [5]. The tangential force F_{r} component is calculated using magic formula tire force model [3],[4] with F_{N} and the slip λ.

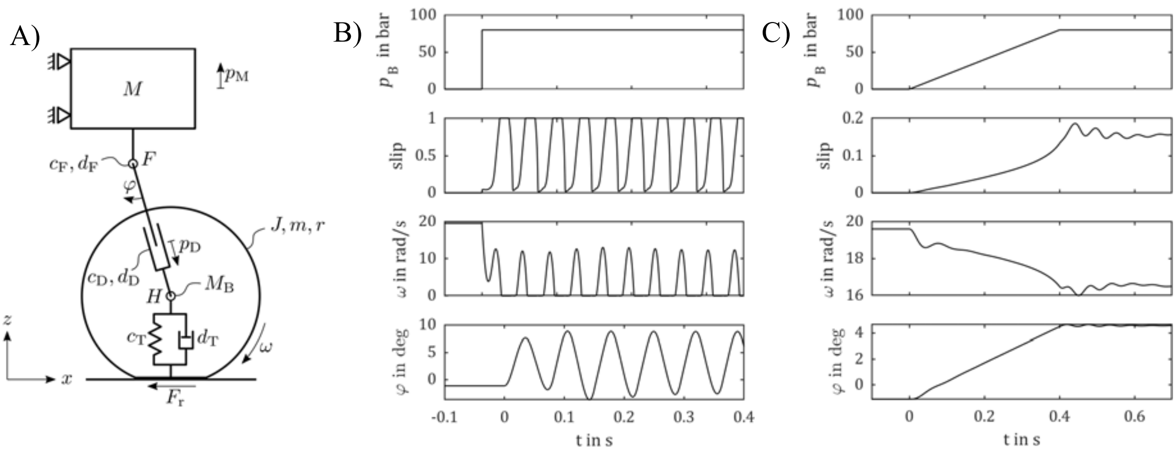

*Figure 2: **A** Topology of the used multibody simulation model. **B** Simulation results with step function 0-p_B **C** Simulation results with ramp 0-p_B, rising slew rate of $200\ bar/s$.*

The following two braking situations with constant bicycle velocity $v_0 = 7\ \mathrm{m/s}$ where simulated: First, a step from zero to $p_{\mathrm{B,krit}}$ is applied. With $p_{\mathrm{B,krit}}$ being the maximum theoretical possible brake pressure without wheel lock up. Second, the same step to $p_{\mathrm{B,krit}}$ is applied but with a rising slew rate of $200\ \mathrm{bar/s}$. The results of the two simulation runs are depicted in Fig. 2.

4 DISCUSSION AND CONCLUSION

The simulation shows self-oscillations on the slip λ, wheel speed ω and fork bending angle φ when the brake is applied with a step function. Contrary, when a rising slew rate is set, the self-oscillation is not kickstarted. A more in-depth analysis showed that the average braking force is 33 % lower if there is self-oscillation compared to the non-oscillating case. In fact, the step must be reduced to 88 % $p_{\mathrm{B,krit}}$ to prevent starting the self-oscillation.

The oscillatory motion was further analysed, there is a hopping motion present as depicted in Fig. 3. It can be described as follows: the fork is bend against the braking direction due to the braking force (1). The geometry of the forwardly inclined fork loads the tire and accelerates the mass M up (2). The tire is faster unloaded from the lifting mass M than loaded by the bending fork, it loses grip and jumps forward (3). Gravity accelerates the mass M down and causes the tire to grip again (4). The process (1)-(4) repeats indefinitely. From a Lyapunov viewpoint the oscillation is supposed to die down because all joints are dampened. Therefore, the hopping must be the energy source driving the oscillation.

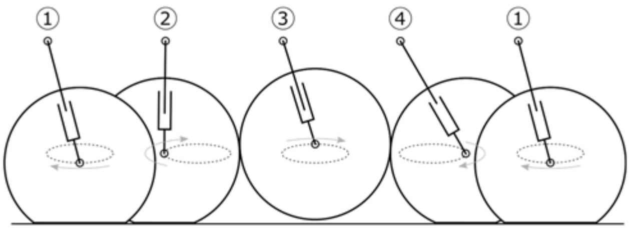

Figure 3: Visualization of the observed fork bending oscillation in the multibody simulation. There are two superimposed motions, the fork oscillates back and forth (2, 4) and the tire bounces up and down (1 ,3) resulting in a hopping motion.

In this work the experimental observed self-oscillation was replicated in simulation making in depth analysis possible. It was shown that the stopping potential is negatively affected by the oscillation and the underlying hopping mechanism was described.

Future research includes active means to reduce the fork bending itself or its detrimental effect on braking performance, for instance with active brake pressure modulation. Also, passive means of oscillation suppression are of interest, such as geometry changes or additional dampers. The fork and tire bending parameters will be measured in detail to enhance the simulation.

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