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Influence of damper control on traction and wheelie of a full suspension eBike with anti-squat geometry

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ABSTRACT

System excitation by the act of pedaling is one key feature that distinguishes vehicle dynamics of bicycles from other vehicles. Elaborate suspension mechanisms minimizing the coupling between longitudinal and vertical dynamics by encorporating anti-squat properties have become common for full suspension mountain bikes. Also, first electronically controllable damper elements are entering the market. This paper evaluates how damper control can improve vehicle dynamics with special respect to traction and wheelie. For this purpose a full vehicle multibody model with slip-based tire model is developed and validated experimentally.

Keywords: vehicle dynamics, full suspension mountain bike, semi-active suspension, multibody modeling

1 INTRODUCTION

The role of suspension systems on bicycles is rather special compared to other vehicles. On the one hand, a majority of bicycles does not have a suspension system at all. Apart from cost and weight issues a reason for this is that, due to the short wheelbase and high center of gravity (COG), suspension systems make the vehicle prone to motion excited by braking, pedaling and motor torque. On the other hand, in the mountain bike field a variety of rather complex rear axis kinematics has become common, addressing anti-squat (reduction of pedal induced dive-in) and anti-rise (reduction of rear brake induced dive-in). In the automotive field this is usually achieved by designing an aligned axle path, so that a component of the longitudinal forces counteracts the increased wheel load. On bicycles the high COG causes a large amount of load transfer that can hardly be compensated by reasonable axis angles. Therefore, the chain force is used additionally. As visualized in Fig. 1, it creates a torque component around the instant center of rotation of the wheel suspending frame component. The geometry is then designed in a way that the three torque components generated by chain force F_{ch}, the proportional drive force F_x and the resulting load transfer $\Delta F_z(\ddot{x})$ are balanced. In the optimal case this goes along with an anti-squat ratio of $100\ \%$. Apart from that also under- or overcompensating setting are possible. A downside of the general approach is that it introduces a coupling between suspension stroke and pedal angle, the so-called pedal kickback. Also the approach is of course not applicable to the front axis, telescopic suspension forks are used almost exclusively.

In scientific literature bicycle dynamics are still a rather little researched domain. Semi-active damper control for bicycles has been proposed by [1, 17, 16]. Due to their focus on actuator-level control the effects of pedaling have not been studied. In [15] the pedal excitation problem is analyzed by multibody simulations and test-bench measurements. In the non-moving environment, the anti-squat properties cannot be addressed specifically. Most scientific work regarding pedaling

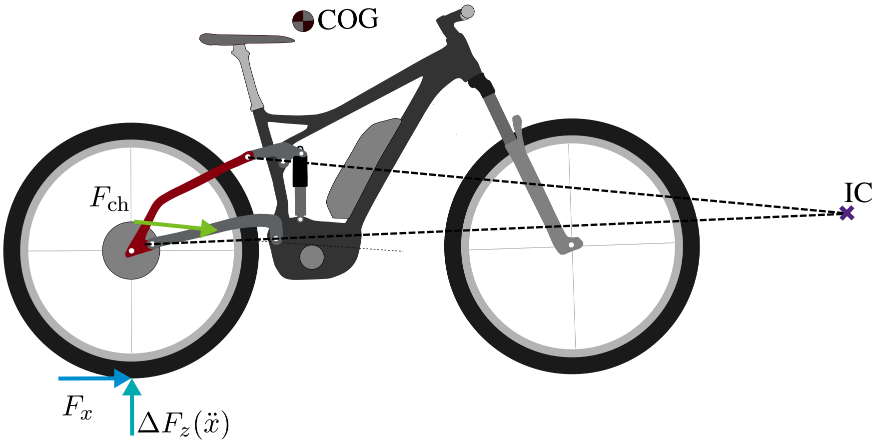

Figure 1. Forces on the rear suspension. Optimal anti-squat requires the resulting moments around the instant center of rotation (IC) to be in equilibrium.

is related to physiological aspects [9, 7, 8, 12, 13]. A very important contribution to understanding and modeling the vertical dynamics of bicycles is provided by [14], where the non-stiff behavior of the rider, the heaviest part of the vehicle, is analyzed. Based on test-bench measurements the dynamic response of the rider is identified and modeled with multibody simulation. In [3] a three-dimensional multibody model of a full suspension mountain bike is presented and used to quantify handling properties. A limitation, however, is the penalty-based tire model that does not allow the analysis of friction limitation.

The contribution of this paper is twofold: First of all, a full vehicle multibody model with slip-based tire model capturing the coupled longitudinal and vertical dynamics under pedal and motor excitation is presented. Secondly, the potential of semi-active damper control is evaluated. Under this objective it is useful to analyze how damping values set to the outer bounds of the feasible actuation range affect vehicle dynamics. This reveals how switching away from the usual soft suspension setting can improve the classical objectives comfort and road-holding. This work focuses on the latter, which can be divided into two cases: If friction is a limitation, traction becomes important, which can be evaluated inspecting rear wheel load $F_{z,r}$ and tire slip λ. Without friction restriction, especially in the presence of road slope, the wheelie situation (loss of front wheel load $F_{z,f}$) introduces an additional limitation caused by the high COG.

The paper provides a systematic analysis of the relevant input-output-relations, evaluating how front and rear damper forces affect traction and wheelie. Special attention is drawn to the influence of anti-squat properties, by altering the geometry to over and undercompensating settings.

The paper is organized as follows: The experimental setup is presented in Section 2. Section 3 describes the developed multibody model and the validation procedure. In Section 4 the model is then used to simulate the relevant situations evaluating the influence of the damping values. Finally the results are summarized and a conclusion and outlook are given.

2 EXPERIMENTAL SETUP

For the purpose of model validation a full suspension bicycle is equipped with the sensors required do capture the relevant variables of vehicle dynamics (Fig. 2). Above that, the test-bike is also a platform for experimental investigations as well as prototypical implementation of control algorithms.

Figure 2. Test bike with measurement setup consisting of drive-integrated torque sensor (1), wheel speed encoders (2), inertial measurement units (3). Additionally, there is the electric drive (4) and semi-active dampers (5) as well as an electronic control unit (6) for logging and prototyping.

3 MODELING AND VALIDATION

This section describes the full vehicle model and the validation procedure. The bicycle is modeled with the aim of describing the system behavior with respect to the excitation by:

- pedaling
- motor torque
- road profile
- braking
- cornering

This paper is focused on the first two system inputs. From a vehicle dynamics perspective the motor can be seen as a pure torque source combined with the respective gear ratio and inertia. The act of pedaling in change can again be separated into two components: First, a pedal torque depending on the pedal angle, which is fundamentally connected to the second component, the rotational imbalance introduced by the shere leg motion. In the following the vehicle model will be described and validated with respect to these two inputs.

The vehicle model itself is visualized in Fig. 3. The main body elements are front and rear wheel, main frame as well as upper and lower part of the fork. The rear suspension system consists of a four-bar mechanism, often referred to as horst-link suspension. The elements are connected by the respective rotary joints. The steering is disabled for the presented in-plane investigation, but can be activated for analysis of curve maneuvers [4]. Front and rear suspension are considered linear spring-damper elements, of which the damper parameter can be changed dynamically.

This pure representation of a mechanism becomes a vehicle model by the additional tire model. In longitudinal direction front and rear tire are represented by the slip-based magic-formula friction description [10]. In vertical direction the tire is modeled as a damped elastic element. The parameters are derived as described in [5].

On bicycles the rider contributes a dominant portion of the entire vehicle mass and also bears elasticity and damping properties [14], which causes huge influence on vehicle dynamics [6]. The

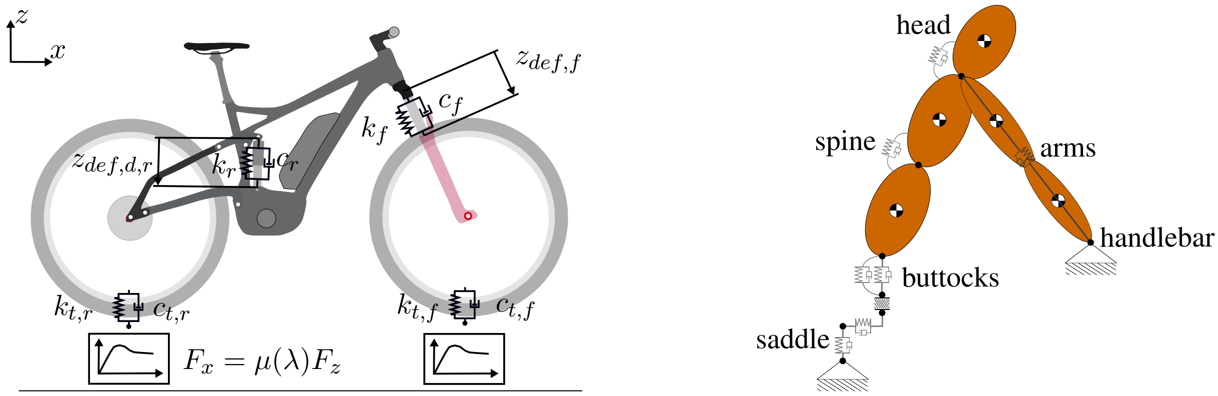

Figure 3. Multibody model of bicycle (left) and rider (right)

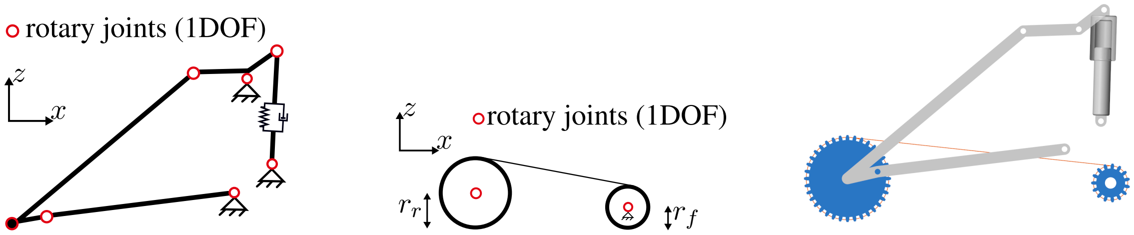

Figure 4. Multibody representation of rear axis kinematics and drive train

rider model is visualized on the right side of Fig. 3. In previous work it has been parameterized and validated by placing sensors on the respective body elements. The complex movement of the arms is approximated by a single spring damper element. It is mainly excited by shocks on the front wheel. Upper and lower body are connected by a single rotary spring element. This accounts for the fact that the spine hardly has any vertical elasticity, it is mainly subject to bending motion. Most shock attenuation from the direction of the rear wheel is actually provided by the buttocks. Measured vertical acceleration peaks of upper and lower spine show similar amplitude. Longitudinal motion on the saddle is represented by a spring-damper element, vertical contact loss between saddle and rider is engaged by a vertical hard-stop element.

The representation of the coupling between suspension and drive train is visualized in Fig. 4. The four-bar suspension kinematic is combined with two chain-pulley elements. To account for the various gears the pinion radius can be changed accordingly.

3.1 MOTOR AND PEDAL TORQUE

Motor and pedals have almost similar influence on the suspension system, when considering the pure torque component only. In order to validate the simulation with respect to system inputs of this type two experiments are conducted: torque pulses in stand still as well as riding uphill.

For the stand still experiment the front wheel is rigidly attached to the ground. This way there is no acceleration-related alteration of rear wheel load $\Delta F_z(\ddot{x})$. As a result, the anti-squat mechanism (see. Fig. 1) is not active and major suspension stroke can be observed. Figure 5 shows that both cases are modeled with reasonable accuracy. It can also be observed that, for comparable pedal torque, the effect is much higher in the lowest gear, which is obviously due to a much higher wheel torque. Also, especially for the lower excitation in the highest gear, a certain friction related component can be observed. As this shows low reproducibility it is not included in the model.

Figure 6 shows a measurement and simulation on an incline with moving bicycle. Observing the

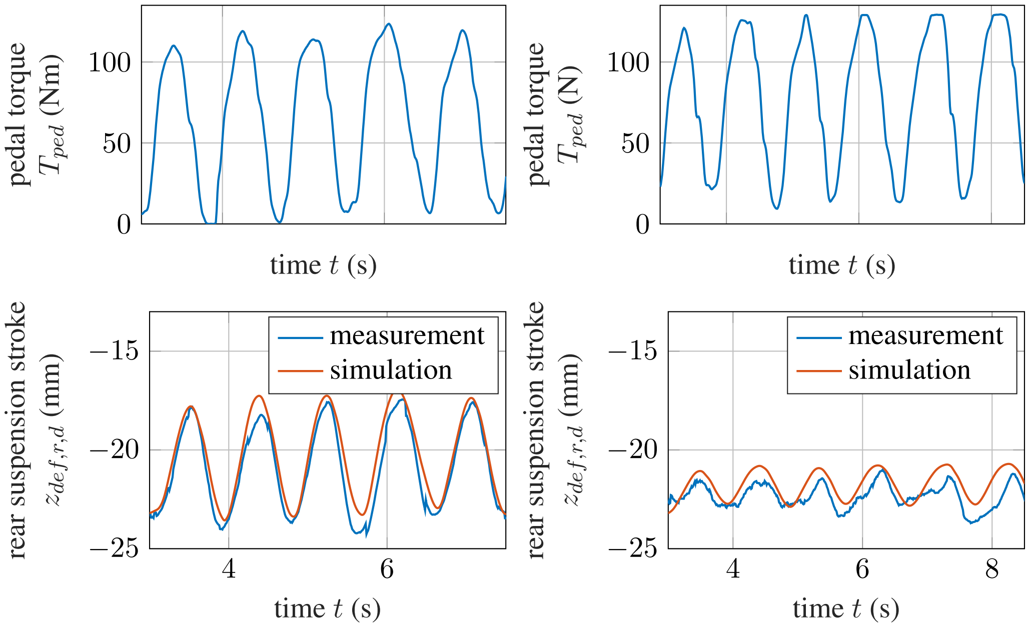

Figure 5. Validation of torque excitation during stand still. left: lowest gear (36T), right: highest gear (11T)

rear suspension stroke it can be seen that the anti-squat kinematics are effective. All suspension related pitch motion can be accounted to the front fork. All relevant signals, the fork stroke $z_{def,f}$ (measured by a stroke sensor), the pitch rate ω_y (IMU) and the wheel speed v_x (incremental sensor) can be considered valid.

3.2 RIDER IMBALANCE

As described above, apart from the pure torque excitation there exists a systematic coupling with rider imbalance. It consists mainly in the circular motion of the legs, but can also contain components of upper body movement. For this paper, only the leg motion is simulated in order to cover the lower boundary of the rider imbalance. The used leg model is shown in Fig. 7. Instead of modeling the complex set of muscular forces that act inside of a human leg, the pedals are simply rotated with a defined velocity profile. At a given cadence, a rider can hardly impose less excitation on the bicycle than described by this simplification. The bodies are modeled in a CAD environment and scaled to match the biomechanical properties in [2, 11].

For validation, a measurement with pedaling but negligible torque is recorded in stand still and while riding. In stand still, the chain has been removed. The measurement during riding was recorded at a slight decline with a negligible pedal torque below 10 Nm. The results are shown in Fig. 8. The two measurements show a certain difficulty for the rider to pedal constantly without load. This causes the slight discontinuities. The simulation is of course not affected by this. Despite this problem with the experimental analysis of separated torque and imbalance excitation, the simulation can be considered valid also in this domain. As expected with the leg only approximation, the oscillation amplitude is slightly underestimated but covers the main effect.

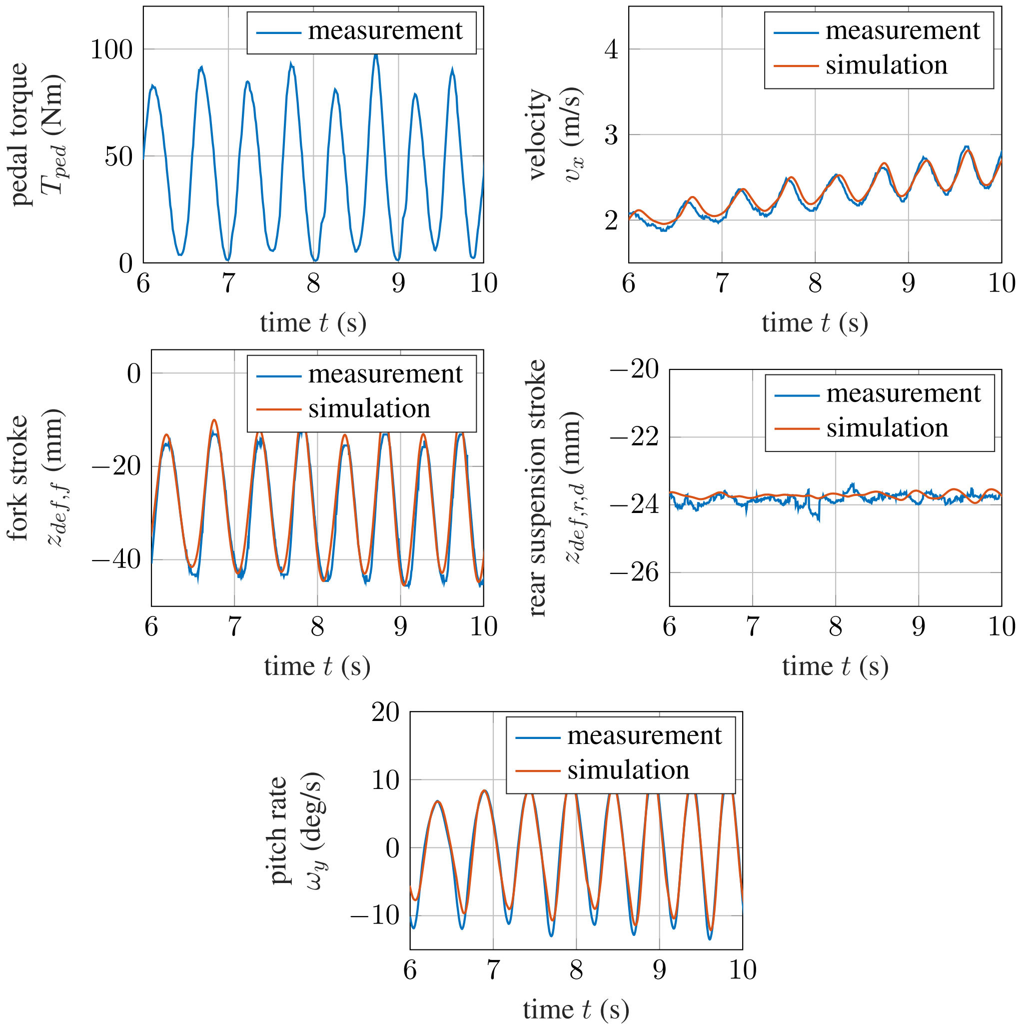

Figure 6. Validation of torque excitation while riding an incline

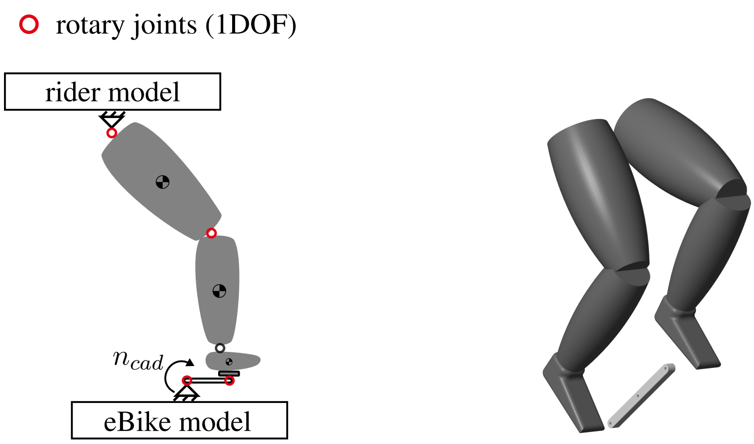

Figure 7. Schematic model of the legs (left) and visualization in the multibody model (right)

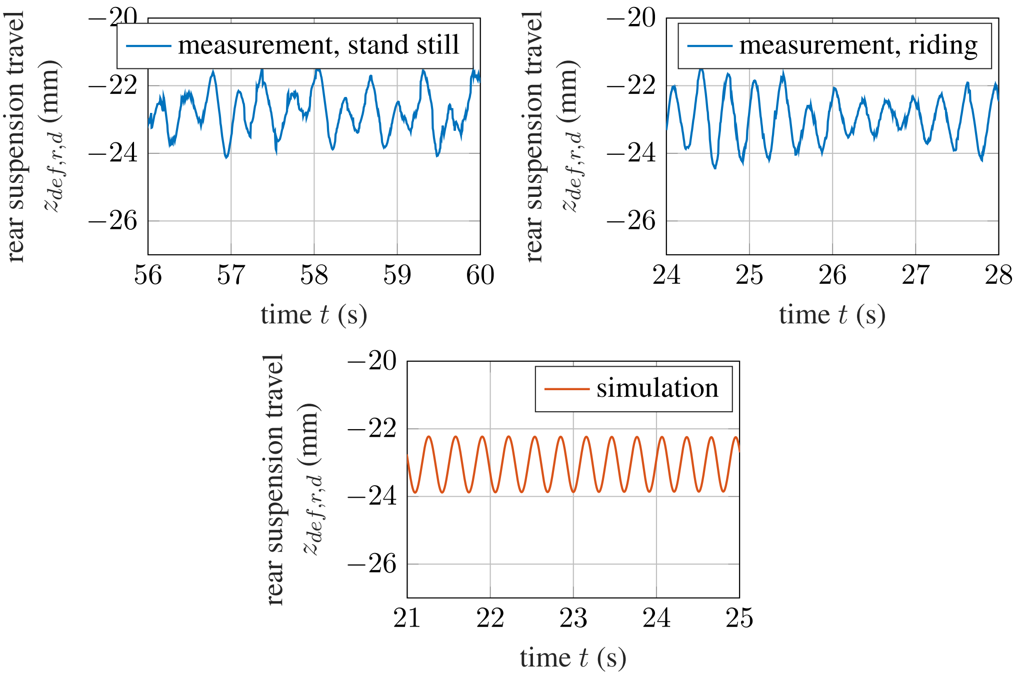

Figure 8. Validation of rider imbalance in stand still (top left) and during riding (top right)

4 SIMULATION AND RESULTS

The validated simulation environment can now be used to analyze how pedal and rider torque affect traction and wheelie. A simulative approach at this point has the advantage of availability of variables that are not accessible experimentally. Wheel load for example can hardly be measured during riding. In the automotive field there exist dedicated measurement wheels, for bicycles they would unreasonably affect the mass distribution. An additional advantage of the simulation is the possibility of freely changing the suspension geometry, away from the decent anti-squat properties of the test bike to under- or overcompensating settings.

4.1 TRACTION

In terms of torque excitation and traction especially the rear suspension is relevant. The dynamics are influenced by two dominant properties: damping value and anti-squat ratio. The first one is the actuated variable of semi-active suspension control. The anti-squat ratio in change is usually a fixed parameter of a specific bicycle, though it may change with respect to the rider's center of gravity and suspension stroke.

The anti-squat ratio can be changed by the geometrical properties of almost every component of the suspension mechanism. At this point the height of the pedal axis is moved in vertical direction by ± 20 mm. The respective simulations are visualized in Fig. 9. Observing the rear suspension stroke under- and overcompensation can clearly be identified. Overcompensation causes an upward motion of the bicycle frame while pedaling. Intuitively this would go along with an improvement in wheel load, yet the opposite can be observed. The reason for this becomes apparent when analyzing the saddle acceleration $\ddot{z}_{sad}$, which indicates the vertical COG acceleration. Initially, there exists a positive acceleration, which also causes an advantage in wheel load. Around the peak pedal torque, where the wheel load also is at its maximal value, the acceleration has already change sign. This goes along with a wheel load disadvantage. However, overall it can be

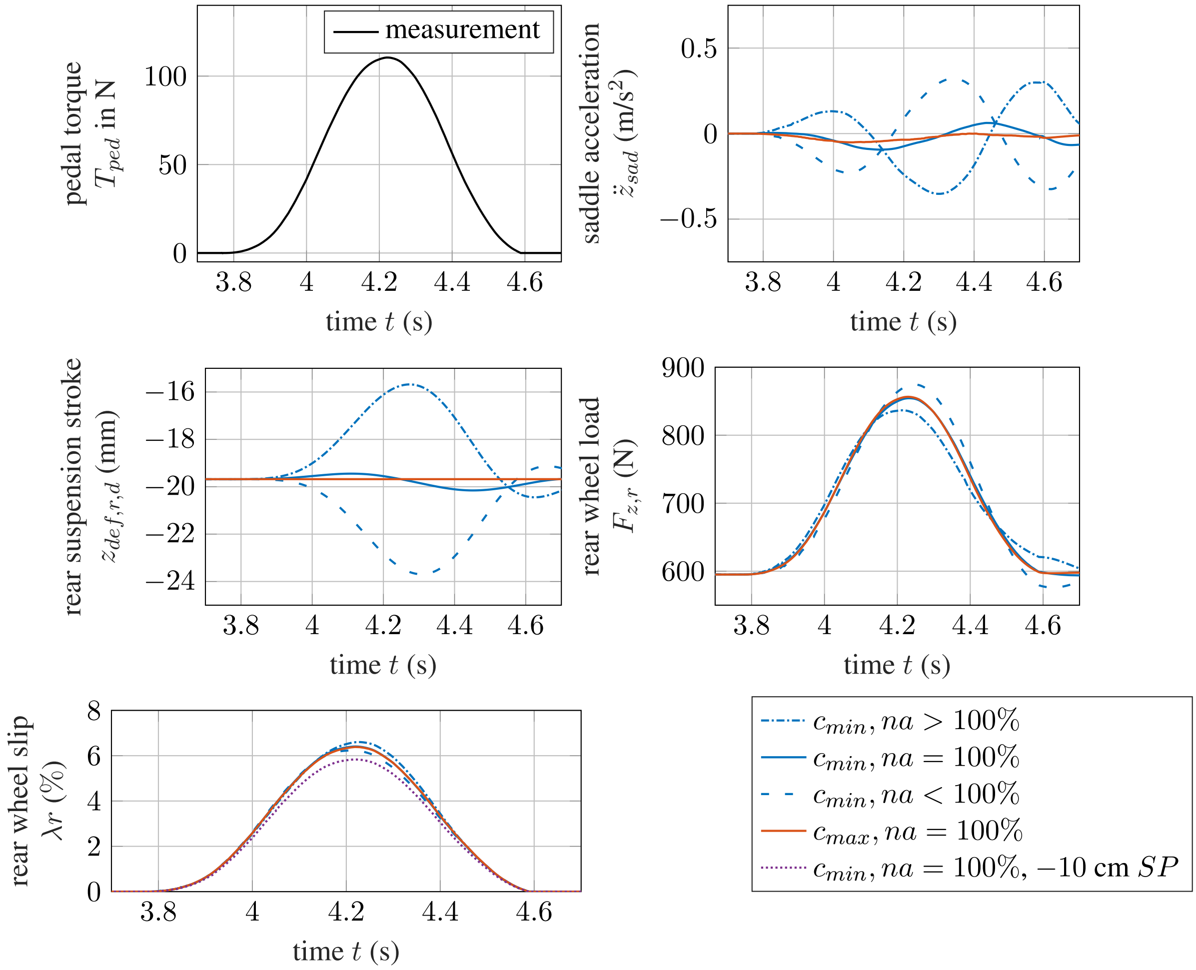

Figure 9. Simulative analysis of the influence of pedal torque on traction

stated that the differences in wheel load and in the resulting slip are rather small. In the simulated maneuver neither different damper settings nor changes in kinematics result in significant traction advantages.

The influence of the rider imbalance is analyzed in Fig. 10. Naturally, the amplitude of excitation strongly depends on the frequency. Therefore a frequency sweep is simulated. On the left side a time window is shown, whereas the right side shows the peak envelope. This can be understood as an approximation of the absolute frequency transfer function. It can be seen that indeed a significant oscillation is imposed on the rear wheel load. The optimization potential that is reachable by changing damper settings is frequency-dependent. The most relevant value for traction issues is the lowest wheel load value. In the lower cadence range it can be changed by roughly 5 %. For a pedaling frequency $f_{ped} > 3.7$ Hz the potential is higher, but a rider will hardly pedal at this cadence (111 rpm).

4.2 WHEELIE

The wheelie situation naturally starts with the front wheel losing its contact to the road surface. From this point on steerability is not given anymore. Additionally, when more torque is applied, the rider can fall backwards. Front wheel contact loss is also the physical limit to longitudinal acceleration and can be compared to the nose-over problematic while braking.

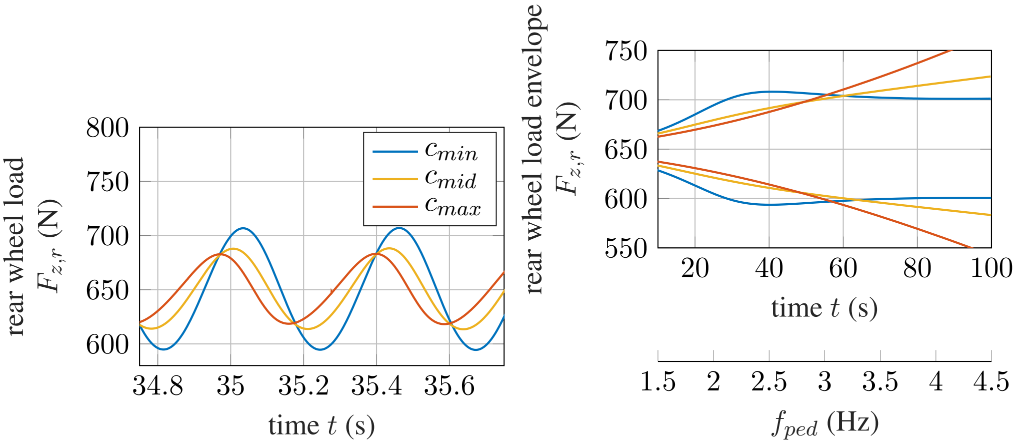

Figure 10. Simulative analysis of the influence of rider imbalance and traction

The pitch dynamics of a fully suspended bicycle with soft damping can be of overshooting nature, the resulting problem is shown in the simulation in Fig. 11. On an incline (14%) with constant motor torque pulsed pedal torque is applied with hard and soft suspension setting. Hard suspension prevents excessive pitch motion. As a result, a certain pedal torque that for the soft setting would lead to front wheel contact loss, becomes uncritical for the opposite suspension setting.

This is of course only a single example. Locking the suspension setting does not guarantee front wheel lift-up mitigation, but allows to apply more torque without the problem to occur. In order to quantify this advantage Fig. 12 shows the outcome of a batch simulation. The result is that 20 % more braking torque can be applied in case of a locked fork.

5 CONCLUSION AND OUTLOOK

The paper provides a systematic analysis of longitudinal vehicle dynamics of an eBike that is subject to pedal and motor excitation. Special attention has been paid to the anti-squat phenomenon. It has been studied on the basis of a 4-bar (horst-link) mechanism, which can of course be extended to various different mechanisms. The anti-squat design worked very effectively in both, simulation and experiment.

In order to evaluate the potential of semi-active suspension control the influence of damper settings on traction and wheelie has been investigated. The influence of rear damper settings on traction should not be overestimated. Also, no major influence of anti-squat has been found. The wheelie phenomenon in change can be significantly affected by damper control. In the researched example the limit for maximal pedal torque when cycling uphill can be extended by 20 %.

Overall, the simulation model is a versatile tool that can also be used for the analysis of comfort and efficiency, also for different situations and actuators, for example brake and motor control. In future the knowledge gained with the simulation, as well as the model itself, will be used for the design of vehicle dynamics control algorithms.

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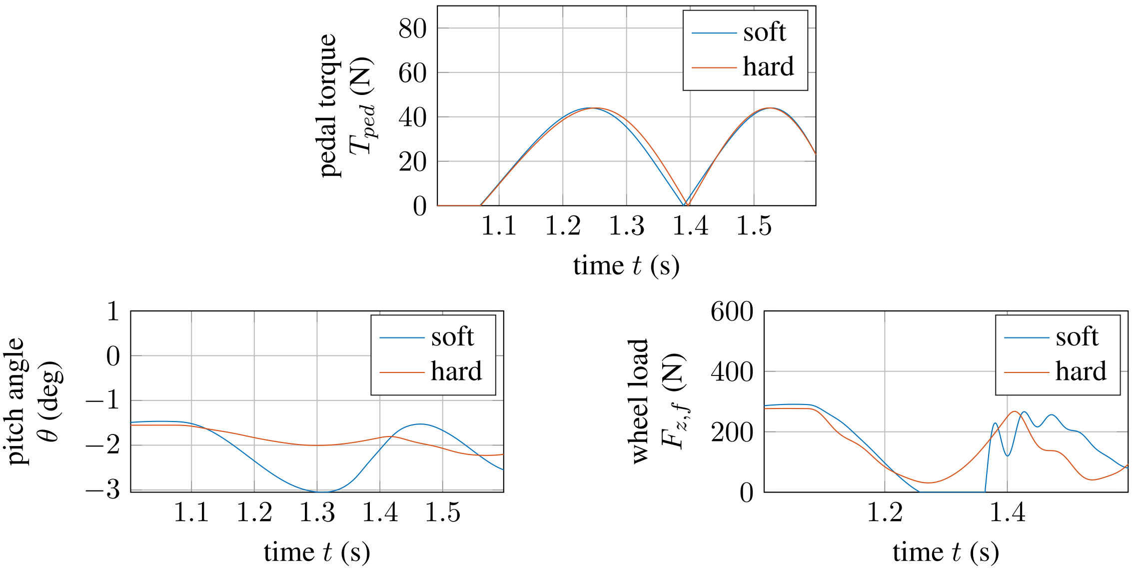

Figure 11. Slope simulation (14 %) with a constant motor torque of 22 Nm and rider peak torque of 45 Nm

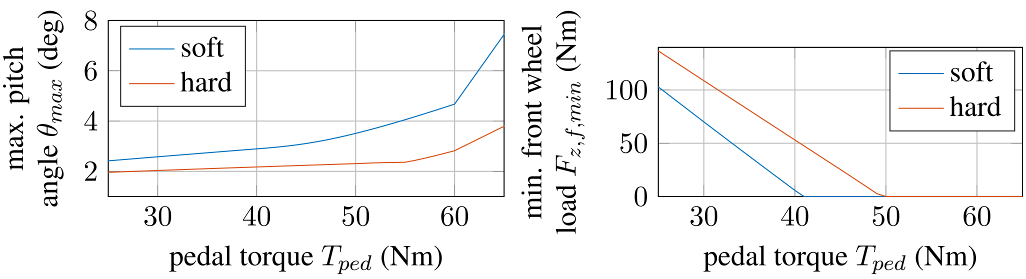

Figure 12. Batch simulation with varying rider peak torque and fork damping

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