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apl. Prof. Dr.-Ing. Daniel Görges (Hrsg.)

Silas Klug

Modeling and Control of Bicycle Dynamics

with Focus on Brake and Suspension Systems

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Band 2

Modeling and Control of Bicycle Dynamics

with Focus on Brake and Suspension Systems

Modellierung und Regelung der Fahrdynamik von Fahrrädern

mit Fokus auf Brems- und Fahrwerksystemen

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Abstract

The ongoing trend of electrification has remarkably extended the operational range of bicycles and also the number of users. Moreover, it is an enabler for mechatronic systems controlling vehicle dynamics. Compared to the automotive and motorcycle field, the dynamics of bicycles are a rather little researched domain. For multiple reasons, like a high center of gravity and a rider who is usually much heavier than the vehicle, it is a very special case of vehicle dynamics, which therefore requires a separate analysis. The aim of this thesis is modeling the longitudinal, lateral and vertical dynamics of bicycles in order to highlight the differences to classical vehicle dynamics, deriving how they affect the control of brake and suspension systems. For this purpose, a multibody model is created, parameterized and validated by realistic road experiments using bicycles instrumented to capture the relevant variables of vehicle dynamics.

Longitudinal modeling allows an evaluation how seatpost movement, brake pressure distribution and fork locking can address brake distance in the critical situations wheel lock and nose-over during brake control. Apart from brake distance, a key benefit of brake control is lateral stability. Here, modeling requires a correct understanding of lateral tire forces. The two most recent publications regarding this behavior of identical bicycle tires have come to vastly conflicting results. A validation procedure conducted in this thesis identifies a correct parameter set, which is a contribution towards stability aware brake control design.

Fork bending and the dynamic response of the rider can be identified as the two dominating effects on coupled longitudinal and vertical dynamics. Fork bending introduces systematic changes to the system and moreover causes measurement errors, both effects severely affect the brake control performance. Methods for error-compensation are accessed experimentally. An analysis of closed-loop control dynamics reveals that pure error compensation does not address the issue expediently, as the errors can also have beneficial effects on closed-loop dynamics.

Due to the dynamic response of the rider, the classical conflict tackled by semi-active control becomes subdominant for typical road excitation. A clear conflict arises when brake excitation is considered additionally. A damper-based anti-dive functionality shows clear advantages on closed-loop brake control. In a case-study with semi-active suspension actuator it is proven that it is possible to implement anti-dive with negligible deterioration of shock attenuation performance.

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Magstadt, June 2019 *Silas Klug*

Notation

Variables

α	Side slip angle
δ	Steering angle
η	Wheel acceleration
λ	Slip
$\boldsymbol{A}$	System matrix
$\boldsymbol{B}$	Input matrix
$\boldsymbol{C}$	Output matrix
$\boldsymbol{D}$	Feedthrough matrix
$\boldsymbol{f}$	Input vector of linearized Whipple model
$\boldsymbol{M}$, $\boldsymbol{C}_1$, $\boldsymbol{K}_0$, $\boldsymbol{K}_2$	Parameter matrices of linearized Whipple model
$\boldsymbol{q}$	State vector of linearized Whipple model
$\boldsymbol{u}$	System input
$\boldsymbol{x}$	State vector
$\boldsymbol{y}$	System output
μ	Friction coefficient
Ω	Spatial frequency
ω	Angular velocity
Φ	Power spectral density
ψ	Yaw angle
σ	Standard derivation
θ	Pitch angle
ε	Error signal
φ	Roll angle
φ_b	Bending angle
a	Acceleration
B_x, C_x, D_x, E_x	Pacejka coefficients
c	Damping value
F	Force

f	Frequency
g	Gravitational acceleration ($g \approx 9.81$ m/s^2)
$G(s)$	Transfer function
J	Rotational inertia
K	Control gain
k	Stiffness value
L	Wheel base
l	Bending length
M, m	Masses, upper case letter referring to the larger one
M_z	Vertical tire torque
P	Cross power spectral density
r	Radius
s	Laplace variable
T	Torque
t	Time
t_r	Rake (distance between steering axle and front wheel axle)
v	Velocity
W	Weighting factor
w	Bending deflection
x	Longitudinal coordinate
y	Lateral coordinate
z	Vertical coordinate

Indices

b	Brake (also: vehicle body, bending)
c	Comfort
r	Road, rear
t	Tire, unsprung mass
act	Actuator
crit	Critical
def	Deflection
de	Decrease
d	Desired/demand
est	Estimated
incr	Incremental
iner	Inertial
in	Increase

long	Longitudinal
max	Maximal
min	Minimal
peak	Peak
ref	Reference
rh	Road holding
sen	Sensor (i.e. measured)
x	Longitudinal
y	Lateral
z	Vertical

Abbreviations

ABS	Anti-lock braking system
COG	Center of gravity
eBike	Bicycle with assisting electric propulsion motor
ESC	Electronic Stability Control
ESP	Electronic Stability Program
ETRTO	European Tire and Rim Technical Organization
IMU	Inertial measurement unit
MIMO	Multiple-input multiple-output

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