

Motorcycle Dynamics

Second English Edition

**Technische Universität Darmstadt
FG Fahrzeugtechnik**

**Inventarnummer:
1943**

Vittore Cossalter

Contents

Foreword	V
1. Kinematics of Motorcycles	1
1.1 Definition of motorcycles	1
1.2 The geometry of motorcycles	3
1.3 The importance of trail	5
1.4 Kinematics of the steering mechanism	9
1.4.1 Steering mechanism with zero fork offset	9
1.4.2 Steering with non-zero fork offset	11
1.5 Roll motion and steering	13
1.6 Motorcycle pitch	15
1.6.1 Pitch in terms of steering and roll angles	17
1.6.2 Pitch as a function of the caster angle	18
1.6.3 Pitch as a function of the normal trail	18
1.7 The rear wheel contact point	19
1.7.1 The effect of camber	19
1.7.2 The combined effect of roll and steering	20
1.7.3 The influence of contact point lateral displacement on roll motion	24
1.8 Front wheel camber angle	25
1.9 The kinematic steering angle	26
1.10 The path curvature	30
1.11 The effective trail in a curve	32
1.12 The effect of tire size on the rear frame yaw	35
2. Motorcycle Tires	37
2.1 Contact forces between the tire and the road	37
2.2 The "Magic Formula" for representing experimental results	39
2.3 Rolling resistance	40
2.4 Longitudinal force (driving-braking)	43
2.4.1 Non-linear model	44
2.4.2 Linear model	45
2.5 Lateral force	47
2.5.1 Lateral force generated by the camber angle	47
2.5.2 Lateral force generated by lateral slip	48
2.5.3 Non-linear model	49
2.5.4 Linear model	50

2.5.5 Lateral force needed for motorcycle equilibrium	51
2.5.6 Dependence of lateral force on load, pressure, temperature	54
2.5.7 Lateral force in transient state	56
2.6 Moments acting between the tire and the road	59
2.6.1 Self-alignment moment	59
2.6.2 Twisting moment	61
2.6.3 Torque generated by the driving or braking force	63
2.7 Combined lateral and longitudinal forces: the friction ellipse	64
2.8 The elasticity of the carcass	66
2.9 Model of the motorcycle tire	68
2.10 Vibration modes of the tires	70

3. Rectilinear Motion of Motorcycles 73

3.1 Resistance forces acting on motorcycles	73
3.1.1 Aerodynamic resistance forces	74
3.1.2 Resistance force caused by road slope	78
3.2 The center of gravity and the moments of inertia	79
3.2.1 Motorcycle center of gravity	79
3.2.2 The moments of inertia	82
3.3 Motorcycle equilibrium in steady state rectilinear motion	83
3.4 Motorcycles in transitory rectilinear motion	87
3.4.1 Acceleration	88
3.4.2 Traction-limited acceleration	93
3.4.3 Wheeling-limited acceleration	94
3.4.4 Braking	96
<i>Role of the rear brake in sudden stops</i>	96
<i>Load transfer during braking</i>	97
3.4.5 Forward flip over of the motorcycle	99
3.4.6 Optimal braking	101

4. Steady Turning 105

4.1 The motorcycle roll in steady turning	105
4.1.1 Ideal roll angle	105
4.1.2 Effective roll angle	106
4.1.3 Wheel velocity in a turn	109
4.2 Directional behavior of the motorcycle in a turn	109
4.2.1 Effective steering angle and path radius	110
4.2.2 Steering ratio	111
<i>Neutral behavior</i>	111
<i>Under-steering</i>	111

<i>Over-steering</i>	113
4.3 Cornering forces	113
4.4 Linearized model of the motorcycle in a turn	115
4.4.1 Critical velocity	118
4.5 Multi-body model of motorcycles in steady turning	120
4.5.1 Mathematical model of motorcycles	120
4.5.2 Simplified model of motorcycles	122
4.6 Roll, steering and sideslip angles	125
4.6.1 Case 1: reference motorcycle	125
4.6.2 Case 2: front tire stiffness (+10%), rear tire stiffness (-10%)	127
4.6.3 Case 3: front tire stiffness (-10%), rear tire stiffness (+10%)	129
4.7 Steering ratio	130
4.8 The torque applied to steering	133
4.8.1 Torque components	135
4.8.2 The influence of motorcycle geometry on the steering torque	137
<i>Normal trail</i>	137
<i>Steering head angle</i>	138
<i>Front tire cross section radius</i>	139
<i>Rider position</i>	139
<i>Tire properties</i>	140
5. In-Plane Dynamics	143
5.1 Preliminary considerations	144
5.2 Suspension overview	145
5.2.1 Front suspension	145
5.2.2 Rear suspension	148
5.3 Reduced suspension stiffness	150
5.3.1 Reduced front suspension stiffness	151
5.3.2 Reduced rear suspension stiffness	152
5.3.3 Stiffness curve	155
5.3.4 Preloading	156
5.3.5 Front suspension stiffness	159
5.3.6 Rear suspension stiffness	160
5.4 Considerations on climbing a step	163
5.5 Slipping of the rear wheel contact point	167
5.6 Models with one degree of freedom	170
5.6.1 Bounce and pitch motion	172
5.6.2 Wheel hop resonance	173
5.7 Two degree of freedom model	174
5.8 Four degree of freedom model	177

5.9	One degree of freedom mono-suspension	182
5.9.1	Oscillatory motion imposed by road irregularities	182
5.9.2	Optimal value of the damping ratio	184
5.9.3	Considerations on single and double effect shock absorbers	186
	<i>Passing over a bump</i>	186
	<i>Passing over a step</i>	188
5.10	Characteristics of shock absorbers	189
5.11	The influence of the unsprung mass	192
5.12	The rear suspension of the scooter	198
5.12.1	Considerations on the position of the attachment point of the engine	198
5.12.2	Attachment of the engine with a rocker arm	200
5.12.3	Rocker arm and link rod attachment of the engine	202
5.13	Road excitation	203
5.13.1	Power spectral density of the road	204
5.13.2	In-plane frequency response function	205
5.13.3	Motorcycle response	206

6. Motorcycle Trim 209

6.1	Motorcycle trim in steady state motion	209
6.1.1	Rear suspension equilibrium	210
6.1.2	Inclination angle of chain	212
6.1.3	Squat ratio and squat angle	213
	<i>Chain transmission</i>	213
	<i>Transmission shaft with universal joints</i>	214
	<i>Four bar suspension with transmission shaft</i>	215
6.1.4	Motorcycle trim as the squat ratio varies	216
6.2	Motorcycle trim in a curve	219
6.2.1	Squat ratio in a curve	220
6.2.2	Trim in entering a curve	220
6.2.3	Trim in exiting a curve	222
6.3	Motorcycle trim in accelerated motion	222
6.4	Influence of rear wheel slippage on the trim	222
6.4.1	Rear suspension with the pinion attached to the swinging arm	222
6.5	The braking action	23
6.5.1	The front suspension	23
	<i>Telescopic forks</i>	23
	<i>Neutral suspension and anti-dive suspension</i>	23
	<i>Four-bar linkage suspension</i>	23
	<i>Push arm suspension</i>	23
6.5.2	The rear suspension	23

7. Motorcycle Vibration Modes and Stability	241
7.1 Simplified model	242
7.1.1 Capsize	242
<i>Model using thin disk wheels</i>	244
<i>Model using tires with circular cross section</i>	246
<i>Model using tires with lateral sideslip</i>	248
7.1.2 Wobble	250
<i>Model of wobble with one degree of freedom</i>	251
7.1.3 Weave	253
<i>Body capsize</i>	254
<i>Steering capsize</i>	254
<i>Model of weave with one degree of freedom</i>	255
7.1.4 Combined model for weave and wobble	258
7.2 Multi-body Model	260
7.2.1 Introduction	260
7.2.2 Motorcycle multi-body model	264
7.2.3 Modes of vibration in straight running	266
<i>Capsize</i>	268
<i>Wobble</i>	271
<i>Weave</i>	272
<i>Rear wobble</i>	275
7.2.4 Modes of vibration in cornering	275
<i>Capsize</i>	276
<i>Wobble</i>	276
<i>Weave</i>	276
<i>Bounce</i>	278
7.2.5 Effect of frame flexibility on modes of vibration	278
8. Motorcycle Maneuverability and Handling	283
8.1 Directional stability of the motorcycle	283
8.2 Gyroscopic effects on the motorcycle	287
8.2.1 Gyroscopic effects generated by yaw motion	288
<i>Gyroscopic effect generated by the wheels during cornering</i>	288
<i>Gyroscopic effect generated by transversally mounted engine</i>	291
<i>Gyroscopic effect generated by longitudinally mounted engine</i>	293
8.2.2 Gyroscopic effects generated by roll motion	295
<i>Gyroscopic effect generated by the front wheel</i>	295
<i>Gyroscopic effect generated by wheels</i>	296
8.2.3 Gyroscopic effects generated by steering	297

8.3	Motorcycle equilibrium in rectilinear motion at low speed	298
8.4	Motorcycle equilibrium in rectilinear motion at high speed	299
8.5	Slow entering in a turn	301
8.6	Fast entering in a turn	303
8.7	The Optimal maneuver method for evaluating maneuverability and handling	305
8.7.1	Optimal maneuver	307
8.7.2	An example of an optimal maneuver for an "S" trajectory	307
8.7.3	An example of an optimal maneuver for a "U" trajectory	310
8.7.4	Influence of the adherence on the trajectory	313
8.8	Handling tests	314
8.8.1	Steady turning test	315
8.8.2	"U" turn test	319
8.8.3	Slalom test	320
8.8.4	Lane change test	323
8.8.5	Obstacle avoidance test	325
8.9	Dangerous dynamic phenomena	326
8.9.1	High side	326
8.9.2	Kick back	328
8.9.3	Chattering	329
8.9.4	Bounce and weave coupling in cornering	330
8.10	Structural stiffness	330
8.10.1	Structural stiffness of the whole motorcycle	331
8.10.2	Structural stiffness of the frame	333
8.10.3	Structural stiffness of the swinging arm	335
8.10.4	Structural stiffness of the front fork	335
8.11	Experimental modal analysis	337
8.12	Rigid body properties and Mozzi axis	338
8.13	Dynamic analysis with multi-body codes	341
List of symbols		343
References		349
Index		353